OPTICAL INSTRUMENTS

by

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with a Foreword by

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Illustrated by the Author

1945
CHEMICAL PUBLISHING CO., INC.
Brooklyn N. Y.

FOREWORD

World War II has already witnessed a development of optical instruments scarcely contemplated a few years ago. Military men are provided instruments for field use in many cases more versatile and precise than those prized by scientists only a few decades ago.

The modern optical instrument is the outgrowth of innumerable hours of study and practice. All the knowledge of materials and techniques gained from a host of individual researches is applied to the final product. To mention only a few, we have prevention of corrosion, optical blackening, quality of paint finish, dust control, heat treatment, ground surfaces, and a steady increase in accuracy of all parts. Even in the art of annealing glass, it has recently become possible to control optical constants with great precision and to provide designer and manufacturer with glass of exceedingly uniform characteristics.

One of the most spectacular successes of the war years is the general application of non-reflecting films to optical surfaces. No scientist need worry now about inefficiency in an optical system of many elements. Then, too, the development of rare-earth glasses of unusual optical properties will prove advantageous to scientific instruments in years to come.

The military instrument is subjected to almost every kind of climatic condition, often in quick succession, and to mechanical shock never encountered in the scientific laboratory. The ordinary motion-picture projector, long a familiar object in the home, has broken down repeatedly in far flung parts of the world. Many such projectors, and optical equipment in general, have deteriorated right in the warehouse. Consider

as another example the mammoth battleship range finder with its multitude of lenses and prisms. A salvo of 16-inch guns imparts a mechanical shock of drastic proportion to such an instrument, and yet, the ranging throughout a battle requires angular accuracy of a very few seconds of arc. Another outstanding example is the aerial camera that, on the ground, is exposed to moisture, fungi, insects, and dust, and, in the air, to temperatures ranging from 160 above to 70° below zero, to rapid temperature changes, to a succession of ice, fog, and air blast, and to mechanical shock from vibration, machine gun and cannon fire. A scientist would never wish to see an instrument of precision so roughly treated. Indeed, military necessity may dictate unloading equipment in heavy surf, throwing packing cases overboard, and exposing instruments to general neglect beyond belief.

The reader is fortunate to have at his disposal a volume full of information on so many kinds of optical instruments. The author's emphasized desire to impart to the reader a knowledge of and admiration for the precision instrument is sufficient justification for the book, in itself. One must learn sooner or later that optical surfaces are not like windowpanes, and that tinkering with instruments is a forbidden pleasure. No other person, not even an optician, understands a given instrument as well as its manufacturer. Do not emulate the man who crossed the threads on a lens retainer ring, and then, being in difficulty, hammered the ring against the glass.

The beginner in optics is likely to be submerged at first by a wealth of practical detail and theory. Optics may even seem ponderous and unexciting. One's interest grows mostly by using optical equipment. The ancient scientist was delighted by such simple phenomena as mirror reflection and the burning glass. Yet here at the reader's disposal is a highly developed optical science for the purposes of quick understanding. If each reader learns from this volume an understanding of the

instruments near at hand, the book will have accomplished a most practical and useful purpose.

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INTRODUCTION

THIS BOOK HAS BEEN written in an effort to fulfill the need for a volume which will make a reasonably thorough coverage of the general field of optical instruments. Present volumes are either restricted to a thorough coverage of one instrument or of a small group of similar instruments, or to a theoretical discussion of optical principles. It is felt that a volume which discloses the basic principles of design, function, and adjustment of the various common types of optical instruments will find valuable use.

This volume has been written primarily for the individual who comes into contact with optical instruments as a student, operator, teacher, engineer, or repairman. It is not intended for the optical or mechanical engineer, nor as a manual of instruction for the use and care of any particular instrument. The author has attempted to present the broad field of optical instruments as a related whole and to prepare a volume which will be of value and interest to students and teachers in schools and industrial plants, personnel of military and civil establishments, workers and repairmen whose occupation has brought them into contact with various types of optical instruments which it would be to their interest and advantage to understand. The material has been so organized as to make it possible to use the volume as the text for a course in "Familiarization with Optical Instruments," although this is not its principal purpose.

Optical instruments have been increasing in importance in industrial and scientific life for two centuries, and the last two decades have seen them become more and more as integral a part of our civilization as motor vehicles and electrical appli-

ances. The present war has done a great deal to bring home to many individuals the supreme importance of optical instruments and at the same time, it has revealed the extent of their ignorance about these essential tools of war. and peace. The number of individuals who understand the fundamental principles of optics is by no means as large as the number of those who understand the principles of radio sets and internal combustion engines. The individual who would not hesitate to grind the valves of his automobile or replace a condenser in his radio set would not have the knowledge or the courage to take apart his camera or his binoculars, and if he attempted it would run into insuperable difficulties in readjusting the instrument upon reassembly, if, indeed, he realized that adjustment is necessary.

The basis of an understanding of optical instruments is, of course, an understanding of optics, hence the space in the volume devoted to the theoretical treatment of this subject is considerable. Nevertheless, it has been written with the greatest economy of words, and every attempt has been made to treat an essentially mathematical subject in such a way as to make it comprehensible to the reader whose mathematical equipment is meager. This has been accomplished, in part, by placing the more complex mathematical proofs in a special appendix, which may be ignored by those willing to accept the conclusions on faith. Part I may be difficult for those readers whose mathematical and scientific background is not extensive, but it is extremely important and its careful study will be rewarded.

Considerable emphasis has been placed on the telescope, as by far the majority of optical instruments is telescopic in principle. It has been intended to give the reader an understanding of the relationship of magnifying power, field of view, illumination, aperture, and focal length. The chapter on the spectroscope is extensive, as this extremely important instrument is not nearly well enough understood. The section on military optical instruments, although it is the field in which the author's

experience has been most recent, is necessarily incomplete. It has been made as comprehensive as possible without the revealing of restricted military information. Emphasis has been placed here on the purpose and use of these instruments and the general type of optical systems encountered. The chapter on the range finder is, the author believes, as comprehensive as will be found in any published text.

Much material has been included on the care and maintenance of optical instruments, as it is expected that this phase of instrument association will be of particular value to the average reader. Methods of collimation, adjustments for parallax, tilt, double vision, etc., are covered in considerable detail, as well as repair and adjustment of mechanical instrument parts, including set screws, worms and worm wheels, scales, level vials, silvering, and sealing.

Chapters have been included on the fabrication of optical elements, the manufacture of optical glass, and the design of optical instruments, in order that the reader may obtain a clear and complete picture of the optical instrument field. A final chapter has been added on material which is not pertinent to the discussion of optical instruments but which is necessary to answer natural curiosities on the part of readers. This includes brief discussion of some of the principles of physical optics, optical illusions, mirages, the rainbow, and similar phenomena.

Throughout the text, the readers have been referred to certain sections of this book, where the respective subject is discussed in detail. Numbers in parentheses indicate the pertinent section.

The author wishes to give grateful acknowledgment to the following individuals for their valued assistance in the preparation of this book: to Charles and Helen Federer for voluminous and painstaking work in editing the manuscript and reading proofs; to Dr. James D. Baker for important suggestions regarding subject matter and for writing the Preface; to Sergeant Harold Fogel and Walter A. Howland for assist-

ance in preparation of the original draft and the diagrams of Part I; to Captain A. L. Kobernat, Lieutenant J. H. Gains, Staff Sergeants Harold L. Dibble, Roy L. Mullins and Edwin B. Mick, and Sergeant John A. Brink and the author's other associates at the Santa Anita Ordnance School for their help and encouragement in the undertaking.

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PART I

PRINCIPLES OF GEOMETRICAL OPTICS

CHAPTER I

Nature of Light—Sources—Media—Elementary Definitions

1. Luminous Bodies

Virtually all our information about the world around us is brought by light. The existence of illumination and the sensation of sight are so natural to us that we understand them intuitively, and, therefore, seldom take the trouble to describe the phenomena precisely.

Light is energy, the form of which we shall mention in 4. The original source of any light is, of course, some self-luminous body, such as the sun or an electric filament. But we quite generally, in optics, speak of a *source of light* with the intention of referring to any body from which light is emitted, whether originally by self-luminescence, or by reflection of the light from some other body. Now a source of light, a luminous body, can be considered to be made up of innumerable tiny elements, essentially points, each of which can be considered as a separate and independent source of radiation. In geometrical optics, all luminous or illuminated objects are thought of in this way, and this principle has an important bearing on the function and operation of optical instruments, as we shall see. Each point on a body which is emitting light sends out an infinite number of rays in all directions, and each point operates as if the others were not present. This condition is true whether the body is self-luminous or not.

2. Optical Media

An *optical medium* is, strictly speaking, any space, whether or not occupied by matter, in which light travels. In geometri-

cal optics, the assumption is always tacitly made, except when expressly noted to the contrary, that any given medium is *isotropic,* the same in all directions; so that whatever direction light may take, it is equally affected by the medium. In any such medium, all the light rays given out by a point source will be propagated continuously and without deviation so long as they remain in the medium. In geometrical optics, optical media are also assumed to be perfectly transparent; there is no loss of light energy in traversing the medium from one point to another. This is never strictly true, but consideration of the quantities of energy involved in the propagation of light does not lie in the domain of geometrical optics.

For every optical medium, there is an associated definite velocity at which light travels within it. This velocity is less than the velocity of light in a vacuum, and varies with the wave-length (5). The *optical density* (24) of a medium refers to this velocity. In media of high optical density, light travels slowly; in media of low optical density, it travels more rapidly. Optical density is not synonymous with physical density. It is measured numerically by the *index of refraction* (22,25).

3. The Rectilinear Propagation of Light

Among the first facts about the world, which we learn as infants, is that we cannot see around a corner, that we can see through a straight pipe but not through a crooked one; in other words, it is a familiar and well-established fact of our observation that light travels in a straight line (in an isotropic medium). This empirical law is the very foundation of some of our most precise methods of measurement; indeed, the most rigorous demonstration that a line is straight consists of proving that it is the path of light. Such a straight line, indicating the path of light, is called a *ray,* and rays of light, in an isotropic medium, are straight lines.

This is perhaps the most elementary property of light, yet it is the very cornerstone of geometrical optics, because it

permits the application of the precise methods of geometry to the phenomena of light. The principle is known, in scientific language, as the *rectilinear propagation of light.*

An interesting demonstration of this is observed in the pinhole camera. This consists of an opaque screen in which has been pierced a very small hole. This screen constitutes one side of a light-tight box, whose opposite side is of ground glass, tissue paper, or other suitable translucent material. If the box is placed before a strongly illuminated or luminous object, such as a candle flame or an electric lamp, then from each point of the object, a narrow cone of rays will pass through the pinhole and illuminate a small area of the translucent screen. A neighboring point on the object will give rise to a similar cone of rays, which will illuminate an area on the translucent screen contiguous to the first area. Thus, for each point on the object, there is a corresponding area on the screen, and hence a picture of the object will be built up, point by point, on the screen. The picture is geometrically the same as the object, except in size, and it can be shown that a straight line passing through the pinhole from any point on the object will intersect the corresponding point on the screen. The picture will, of course, be inverted in two planes (10). This is not an *image* in the true optical sense, but it can be produced only if light travels in straight lines.

If the pinhole is too large, the tiny illuminated areas on the screen will be too large, and they will overlap to such an extent that the definition of the picture will be ruined. If the pinhole is too small, diffraction effects (chapter XXXIII) will enter. For best results, according to Abney, the diameter of the pinhole would be 0.008 times the square root of the distance of the screen from the pinhole (dimensions measured in inches). The translucent screen may, of course, be replaced by a photographic plate, and a picture secured.

4. The Nature of Light

The exact nature of light is a question which has baffled physicists for many centuries, and is still far from solved. Geometrical optics, however, is not interested in the nature of light. For its purposes, it requires only that the principle of rectilinear propagation should be true; that the representation of rays of light by means of straight lines should be justifiable.

Whatever the actual nature of light is disclosed to be, the final explanation must of necessity involve most of the principles laid down by Christian Huygens in his wave theory of light. Huygens described light as a transverse wave motion.

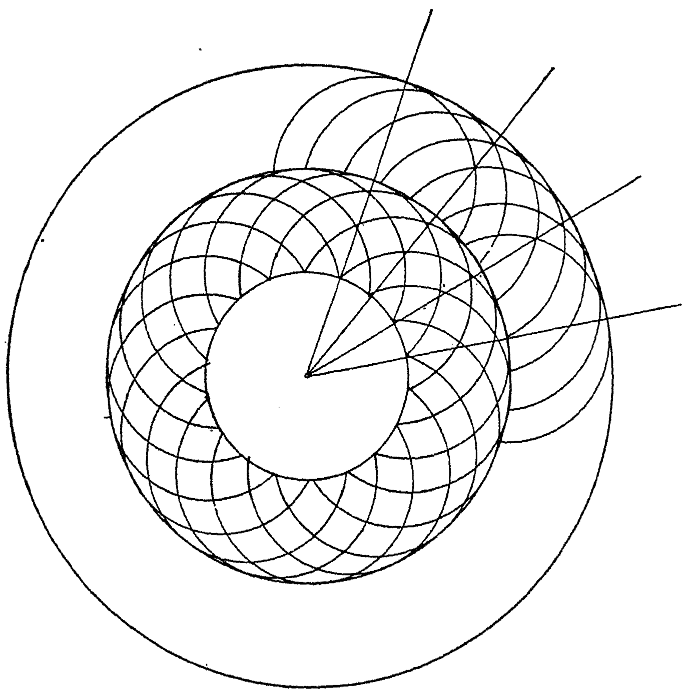

FIG. 1

Huygens' construction of wave fronts

Each point on a luminous body, according to the theory, gives rise to a series of concentric spherical waves, expanding at a definite velocity. The surface enveloping all the most distant points to which the energy has traveled at a given instant is called a *wave front.* In the construction of this motion, each point on a given wave front acts as an independent source of waves or wavelets, and the surface enveloping all these little wavelets at a given instant constitutes the new wave front (fig. 1). The result of such a construction is a new wave front exactly the same as would be obtained by an expansion of the original wave front to that point. The effect of such little wavelets at a given point will be exactly the same as would be the result of the successive disturbances taking place over a straight line (ray) joining this point with the original point source of the light (appendix I). This demonstrates that the wave theory upholds the acknowledged fact of rectilinear propagation (409).

5. Characteristics of Light

There are a few descriptive terms and essential characteristics of light with which the reader should be familiar. The *velocity* of light in free space (vacuum) is about 300,000 kilometers (186,000 miles) per second. In media other than a vacuum, light travels with lower velocity; for example, in water it travels at approximately 225,000 km/sec; in ordinary glass, 200,000 km/sec, etc. In any given optical medium, the velocity of light is constant at all points.

The *wave-length* of light is the distance between successive wave fronts of the same *phase,* the phase of a wave being the degree of displacement of the particles of the transmitting medium. In the case of visible light, the wave-lengths range from 4×10^{-4} to 8×10^{-4} mm. The customary unit of measurement of wave-length is the *angstrom,* contracted Å, which is equal to 10^{-8} cm, or 0.00000001 cm. The *frequency* is the number of wave fronts passing a given point in a unit of time

(usually a second) and is evidently equal to the velocity divided by the wave-length. The color of light is determined by the wave-length (or frequency), the wave-lengths being longest in the red and shortest in the violet. Radiation of exactly the same character as light exists over a theoretically infinite range, and examples are known ranging from the cosmic rays to radio waves of wave-lengths measured in miles. All this radiation is exactly the same as light except for wave-length, but since the human eye is not sensitive to it, it is not usually referred to as light. The term *visible light* is usually used to refer to that portion of the radiation which is detected by the human eye.

When light is traveling in a medium in which its velocity is less than its velocity in free space, the frequency remains unchanged, but the wave-lengths become shorter. In media other than a vacuum, the velocity of light is different for different wave-lengths, being greatest for red light and least for violet. This phenomenon results in dispersion (104). The phenomenon of color sensation occurs in the eye and brain, and is, of course, linked up with the wave-length and velocity peculiar to the vitreous humor (95).

6. Rays of Light

In the case of a single point source of light in an isotropic medium, the waves spread out in concentric shells, and the form of any wave front surface is a sphere, with its center at the point source. In passing the boundary of a different medium, the form of the wave front may be changed, but in any case the direction of transfer of energy is perpendicular to the wave front at a given point. Thus, a ray of light, passing through successive and different media, may be bent abruptly at the surface of each medium (chapter III), but at any point on the ray, the direction of the ray is normal (perpendicular) to the wave front surface at that point. According to the principle of Fermat, the path of a ray of light represents the shortest possible *optical path;* the route which contains the minimum

number of waves between any two given points. It is now known that sometimes the path is not a minimum, but a maximum, but it is always one or the other.

7. Law of Intensity

It is a fact of ordinary observation that an illuminated surface is brighter when it is near the source of illumination than when it is far away. It is also evident that in the case of a point source of light sending out waves, the rate of energy flow per unit of time away from the source is constant, but that, since the surface area of the wave front is constantly expanding, the amount of energy per unit area of that surface is dependent upon the distance of the surface from the source. This is expressed in the law of intensity (law of inverse squares), which states that the illumination produced by a given source of light at a given point is inversely proportional to the square of the distance from the source.

8. Physical Optics

It would be beyond the scope of this book to introduce proofs of the validity of the principles stated above, or to enter further into a discussion of the nature of light or the operation of the wave theory. Henceforward we shall deal almost exclusively with rays of light, and the justification for our treatment of them will be assumed to have been accepted by the reader. Suffice it to say that any operations which we perform upon rays of light can be mathematically justified by application of the wave theory of light. For such justifications, the reader may consult some of the many excellent treatises on the subject of physical optics, or any comprehensive text on physics. Chapter XXXIII has been added to this volume, however, to cover some of the more common phenomena which cannot be described in terms of geometrical optics, and about which questions may arise in the mind of the reader.

9. Images

If we look through a window at the view outside, we observe that the direction of the line of sight toward each point in the field of view passes through a certain point on the glass of the window. If we could make each of these points on the glass a point source of light, giving out the same kind and quantity of light as that reaching our eye from the corresponding point in the field of view, we would have, on the window, a perfect picture of the field of view, which would be indistinguishable, optically, from the actual objects themselves. Such an arrangement of point sources in a definite pattern, corresponding geometrically with another pattern of point sources (which in the above example is the outside view), is called an *image,* and it is the principal function of optical elements to produce images of this type.

Therefore, an image of a point is produced whenever a bundle of light rays, originally emanating from that point, is made to emanate from a point located in a different place. It will make no difference to the observer whether the light rays actually pass through the image-point or whether they merely seem to do so, this point being located where the rays would meet if projected backward. In the case where the light actually passes through the image-point, we call the image a *real image*, and in the case where the light rays diverge as if from the image-point, we call the image a *virtual image* (11).

In order to simplify our ensuing discussion of various items we shall frequently refer to the images of single points, but it must be remembered that in the practical sense we will always be concerned with the images of more or less extended fields of view, the aggregations of an infinite number of points.

10. Inversion

When we see our reflection in a mirror, we are obviously seeing an image produced by the mirror. The image in this

case is, of course, virtual, since it lies behind the mirror, and the light does not pass behind the surface. But we also see ourselves in a different aspect than would an observer looking at us from a point behind the mirror. To an observer behind the mirror, our left would be at his right, and our right at his left. As we see ourselves in the mirror, however, our left appears at our left and our right at our right. In other words, our image in the mirror, as seen by us, is *inverted* from left to right in a horizontal plane, or around a vertical axis.

It is also possible to have inversion from top to bottom, that is, in a vertical plane, or around a horizontal axis, without inversion from right to left. There are, therefore, two possible

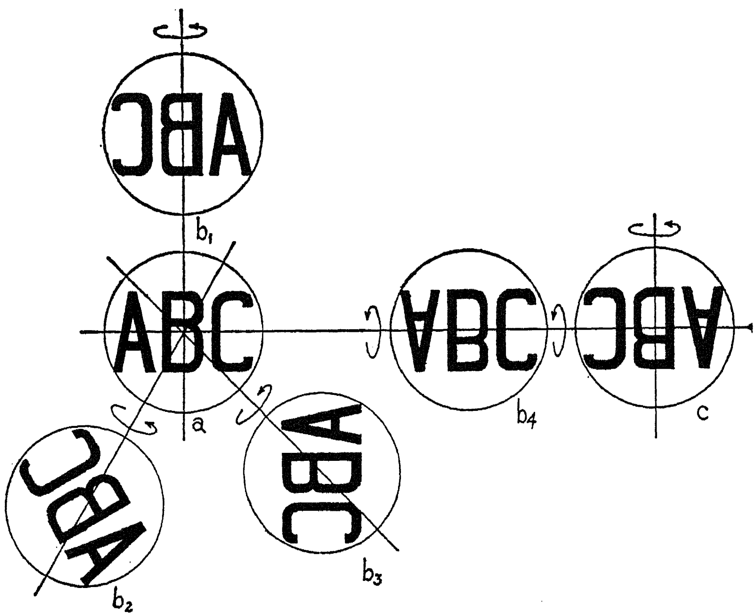

FIG. 2

Inversion

a. No inversion; b_{1-4}. Four cases of inversion in one plane; c. Inversion in two planes. Inversion in *any* two mutually perpendicular planes will yield c.

axes, or planes, of inversion. These two planes are at right angles to each other, but need not necessarily correspond with vertical and horizontal. These are the only possibilities of inversion, and their total number of combinations is three: a. no inversion; b. inversion in one plane; c. inversion in two planes (fig. 2). A given optical element or system may produce an image which is inverted in one plane, in both planes, or not inverted at all. Since the orientation of the optical device in question will, in the case of inversion in one plane, determine in which of all possible planes this inversion takes place, it would be misleading to distinguish any special plane, such as the horizontal or the vertical, by a special name. In some treatises on optics there will be found the word *reversion,* referring to inversion in a horizontal plane. The use of this word introduces an unnecessary confusion. The inversion may be in a horizontal plane or in a plane inclined at any angle to the horizontal, depending upon the orientation of the optical device producing it (84).

11. Location of a Luminous Point

When a ray of light enters the eye, the natural inference is that its point of origin lies somewhere along the line upon which the light entered the eye; if two or more rays are received by the eye simultaneously from a given object-point, then it is assumed that the point source lies at the intersection of the straight lines along which the rays entered the eye.

That this may be an erroneous conception with respect to the true location of the source is shown in fig. 3. Two rays are shown, originating at a point s. At P_1 and P_2 they have been bent by passing into a different medium in such a way that their paths cross at s′. To an eye placed at E, the points seem to be located at s′. Such a point as s′ is called an *image* of s, and it is (9) a *real image* in the case of fig. 3(a) because the rays of light actually pass through the point s′.

In fig. 3(b) a case is shown where the point of intersection

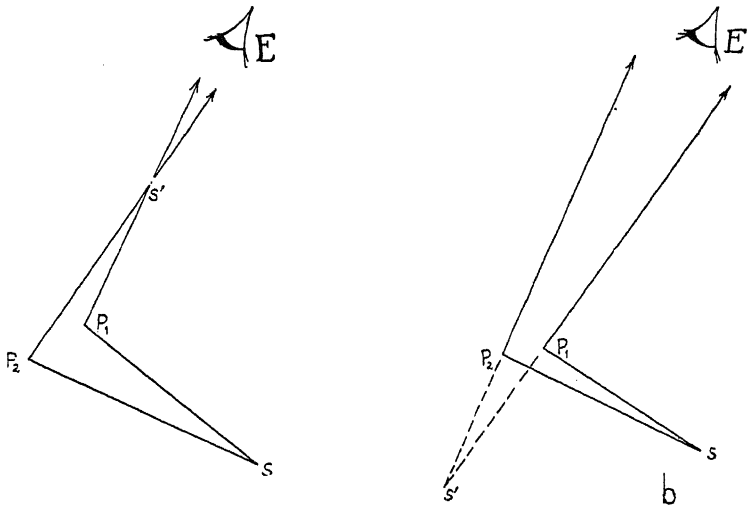

FIG. 3

Real and virtual images; location of a point

of the rays does not lie anywhere along the actual path of the light, but requires that the rays be projected backward to s'. Here, also, the eye at E perceives the point s as being located at s', but in this case the image is *virtual*. Actually, in the case of the observation of a point by the eye, we are always concerned with a great many more than two rays, therefore, the description above does not represent a good conception of the nature of the images formed by an optical system, and this will be taken up in more detail later.

12. Apparent Size

The *apparent size* of an object is measured by the angle it subtends at the point of observation. Apparent size is not to be confused with actual size; the apparent size of a man is far different when we are talking with him than when we see him 50 yards away. The brain has a natural tendency to think in

terms of actual rather an apparent sizes, so that one seldom stops to think of the difference in the apparent size of the man in the two instances. Apparent size is, of course, dependent upon distance; an object far away looks smaller than the same object nearby, smaller in direct proportion to its distance. At 1000 yards, an object looks only 1/10 as large as at 100 yards, and only 1/100 as large as it looks at 10 yards. Hence, we say that *apparent size is inversely proportional to distance.*

13. Effective Rays and the Chief Ray

Although every luminous point sends out rays in all directions, an optical instrument or the eye, cannot make use of all these rays, but of only a relatively tiny bundle of them, limited by the aperture of the instrument or of the eye. This bundle of rays constitutes the *effective rays,* the rays by which the object is seen or with which an image is formed. Each bundle of effective rays contains one ray, called the *chief ray,* which will usually be the central ray of the bundle. This chief ray will be found to be very useful later in determining the course of the bundle as a whole. Any arbitrarily selected ray may serve as the chief ray, and in an instrument it is the ray which passes through some especially selected central point of that instrument. The chief ray of a bundle entering the eye would be the ray which passes through the center of the pupil.

CHAPTER II

REFLECTION

14. Regular and Diffuse Reflection

All substances have the power to *reflect* light (to a greater or lesser degree), to turn it back into the medium from which it came. Light that is not reflected is either absorbed (in an opaque substance) or transmitted (in an optical medium). Most ordinary substances reflect light *selectively,* certain wavelengths (colors) being reflected, while the others are absorbed. This phenomenon accounts for the coloring of ordinary objects, whose hue is that of the light which they reflect.

When the surface from which light is reflected is smooth, the reflection is *regular*; a concentrated beam of light reflected from such a surface will remain a concentrated beam. On the other hand, if the surface is rough, the reflected light will be scattered. This is *diffuse* or *irregular* reflection (fig. 4).

Very smooth surfaces of metal make the best reflectors, and this property is made use of in ordinary mirrors. The glass in a mirror is present merely as a support for the silver coat, which is the real mirror. Such surfaces may reflect as much as 98% of perpendicularly incident light. The reflection from such a surface is, of course, regular.

The surface of a transparent medium will also reflect light, and the proportion of the incident light which is reflected will depend upon the angle of incidence. If the light strikes the surface perpendicularly, there will be little reflection; but if it strikes nearly at grazing incidence, the amount of light reflected will be very great.

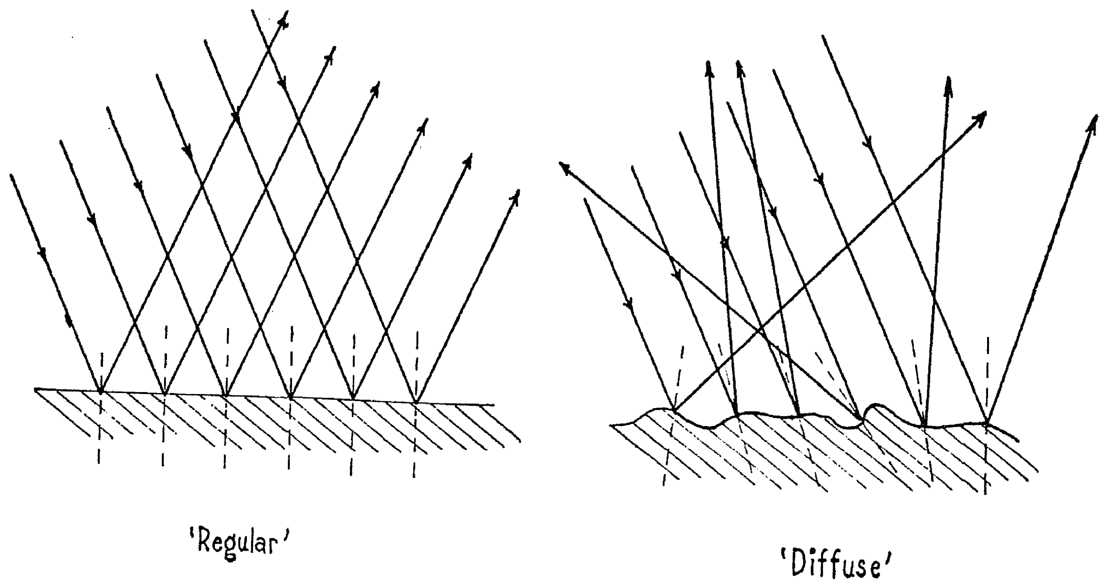

FIG. 4

Reflection

15. Law of Reflection

The law of reflection states that, in any case of reflection, *the reflected ray lies in the plane of incidence,* and *the angle of reflection is equal to the angle of incidence.* The plane of incidence is the plane containing the incident ray and the normal to the surface at the point of incidence (plane of the diagram in fig. 5). The angles of incidence and reflection are the angles made by the corresponding rays *with the normal.* The normal, of course, is the geometrical normal to the surface

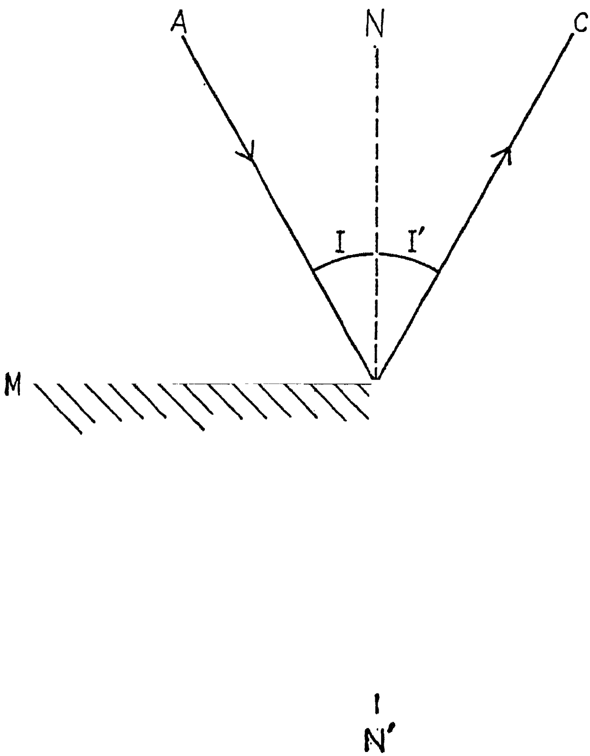

FIG. 5

Law of reflection I = I′

at the point of contact of the ray, the perpendicular to the surface at that point. In fig. 5, AP is the incident ray, PC the reflected ray, NN′ the normal, MM′ the boundary of the media (surface of the mirror), I is the angle of incidence, and I′ the angle of reflection (see appendix I for proof of the law).

16. Image of a Point in a Plane Mirror

A plane mirror will produce a virtual image of a point in such a position that a line joining the point and its image will be perpendicular to the mirror, and the image will lie at the same distance from the mirror as does the point.

In fig. 6, let MM′ be the surface of a plane mirror, and let

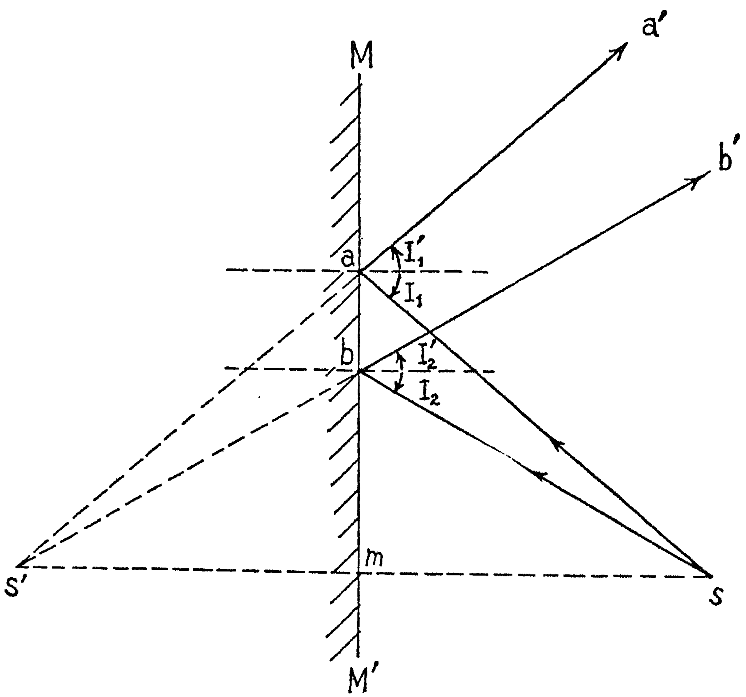

FIG. 6

Image of a point in a plane mirror

s be a point source of light. sa and sb are two incident rays, striking the mirror surface at a and b. The reflected rays will be aa′ and bb′; the angles of incidence will be I_1 and I_2; the angles of reflection I'_1 and I'_2. Now, from the law of reflection (15)

$$I'_2 = I_2 \qquad\qquad I'_1 = I_1$$

It is evident from the symmetry of the construction that a′a produced will meet b′b produced in the point s′, which will be

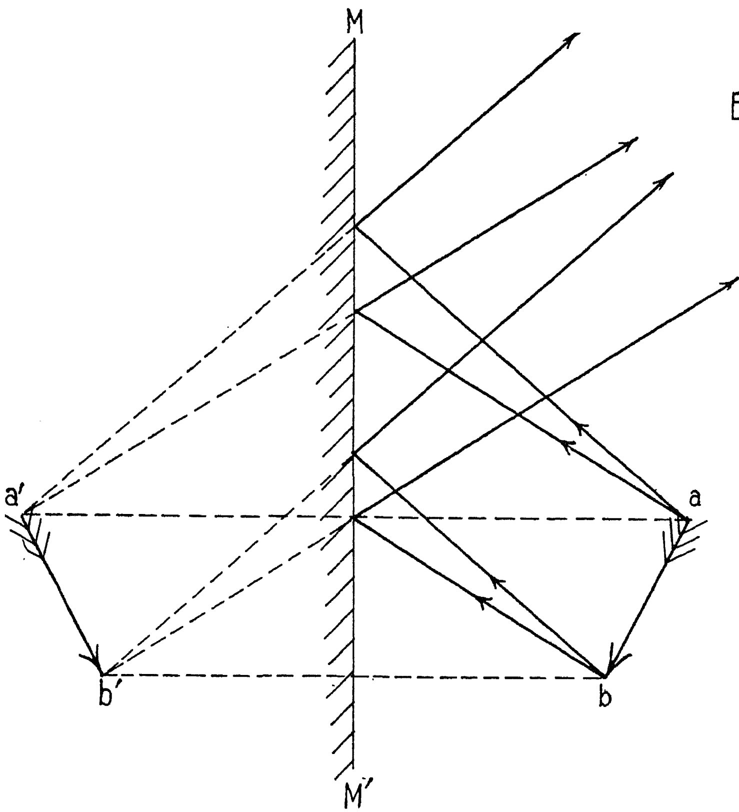

FIG. 7

Image of an extended object in a plane mirror

on the perpendicular sm produced, and that ms′ = sm. s′ is virtual by our definition of a virtual image in (9) and (11).

17. Image of an Extended Object in a Plane Mirror

The image of an extended object in a plane mirror is virtual, is equal in size to the object, each point on the image is on a perpendicular drawn from the corresponding point on the object to the mirror, and each point on the image is the same distance behind the mirror that its corresponding object-point is in front.

For, in fig. 7, let MM′ be the surface of the plane mirror. Let ab be an object. Now, each point on the object may be regarded separately and, by virtue of the proposition proved in (16), the above conclusion follows.

18. Images in a Pair of Inclined Plane Mirrors

If a pair of plane mirrors are inclined to one another at an angle, they will form multiple images of a point located in the angle between them. These images will be located on the circumference of a circle with its center at the junction of the two mirrors and circumference passing through the object-point, and lying in a plane perpendicular to the line of intersection of the two mirrors (fig. 8; appendix I).

In the special case that the two mirrors are inclined at an angle of 90°, there will be three images of any point, s, located in the angle between the two mirrors. There will be an image in each of the mirrors which will be the same as if the other mirror were not present, and there will be another image formed by the rays which have been reflected from both mirrors (fig. 9).

An important property of such a pair of mirrors is that any ray in a plane perpendicular to the line of junction, and which is incident upon both mirrors, will be deviated through 180° and will remain in the original plane of incidence. The "triple mirror" (88) extends this property to rays in any plane.

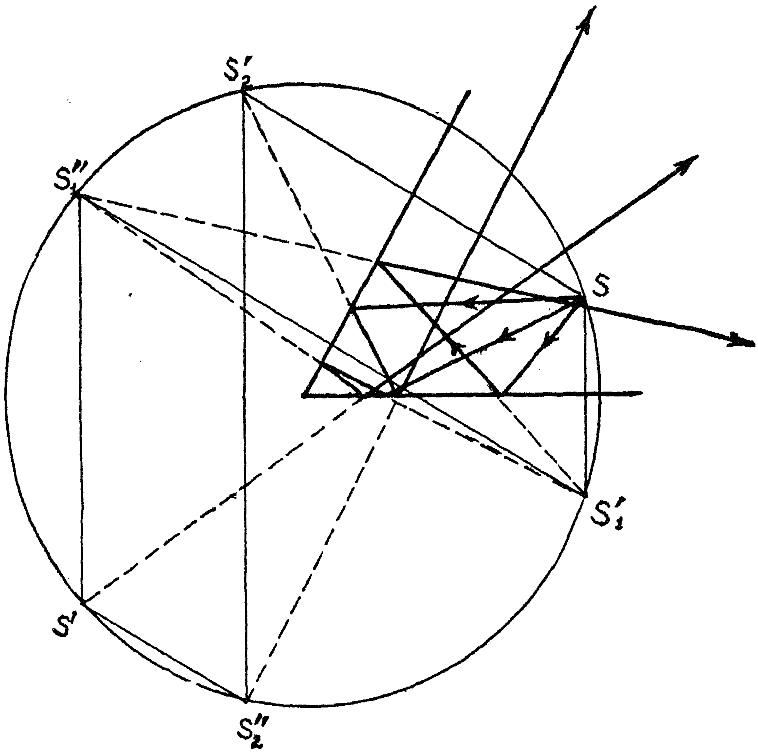

FIG. 8

Images of a point in a pair of inclined plane mirrors

19. Inversion by Reflection

It will be noted that the object in fig. 7 is inverted as seen by an observer at E. Furthermore, the inversion is in one plane only, the plane of the paper. In general, there will be an inversion for every reflection and this inversion will be in the plane of incidence of the central ray. The subject of inversion is quite confusing, and some attempt to clarify it will be made in chapter X.

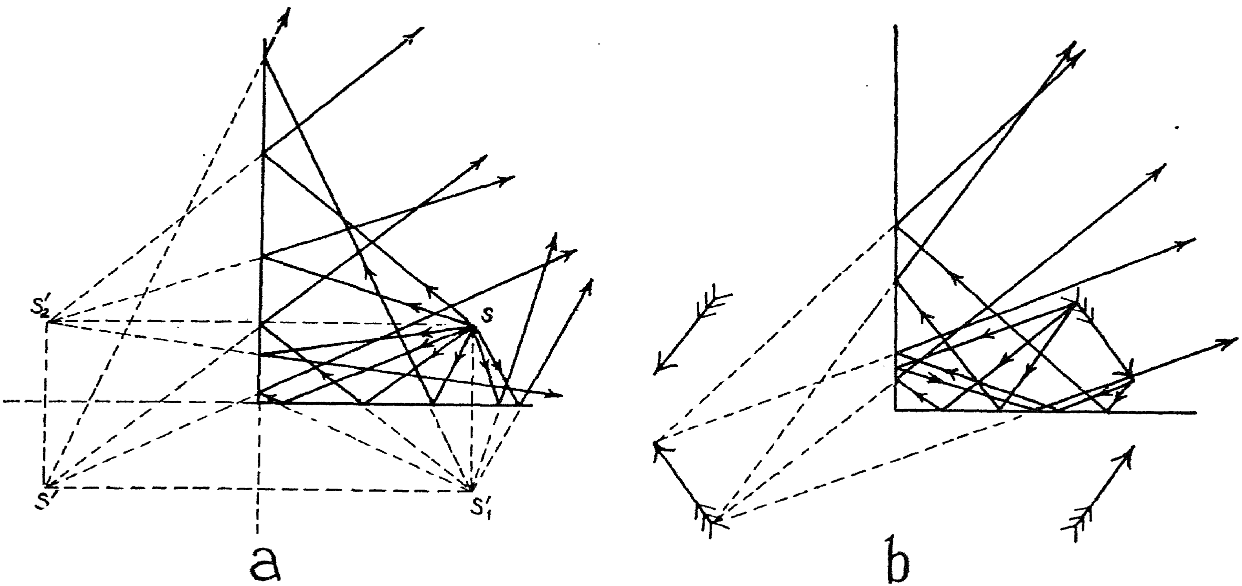

FIG. 9

Images in a pair of mirrors inclined at 90°

a. Images of a point. b. Images of an extended object.

CHAPTER III

REFRACTION

20. Bending of Light at a Surface

When light passes the boundary of two optical media of different density, its velocity changes, and as a result of the change in velocity (except when the light is incident perpendicularly), the direction of the light is abruptly changed. This is best made clear by a momentary recursion to the wave front construction of light.

In fig. 10, AB is a *plane* wave front (from a point infinitely distant) approaching the boundary, MM′, between, e.g., air and glass. Each point of the boundary will then act as an independent source of light according to the wave theory, and will begin to radiate at the instant that the incident wave front meets each particular point. Now, since the wave front AB is approaching obliquely, it will meet the points of the boundary surface *successively,* and point A′ of this surface will start a secondary wave into the glass at a definite time prior to the beginning of radiation from the point B′. Let the arc drawn around A′ represent the expanding boundary of the secondary wave from A′ at the instant that the incident wave front has met the point B′. Since the velocity of the wave in glass is less than that in air, it is evident that the radius of the wave front around A (A′A″) will be less than the distance B_0B'. Also, at a point C′, a secondary wave will have started out after the wave at A′, but before the wave at B′, and consequently has advanced as shown by the arc around C′ (of radius C′C″). It will be seen that the envelope of the arcs around all the points, of which A′, B′, C′ are representative, will be a straight line.

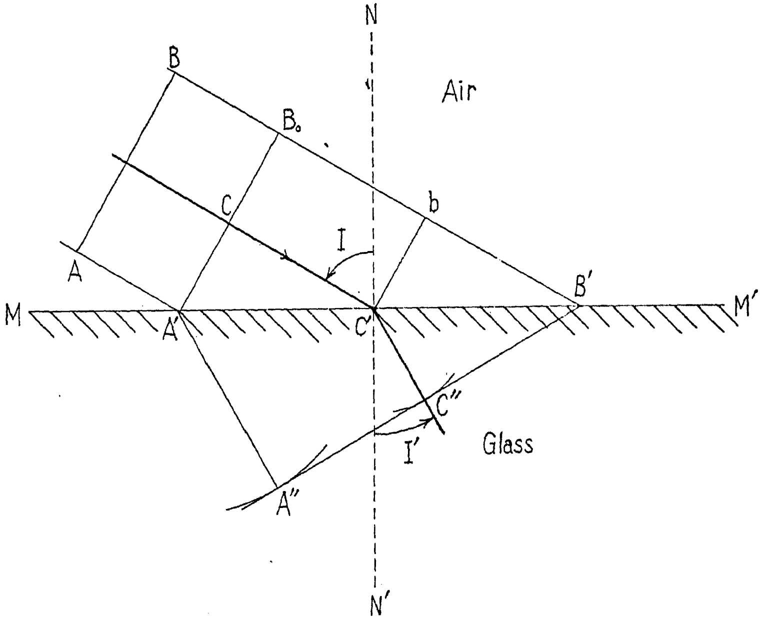

FIG. 10

Refraction of a plane wave

Obviously, then, it is the straight line B′C″A″, passing through B′ and tangent to the arc drawn around A′. This is the new, or *refracted,* wave front, and it will not be parallel to AB unless the light is incident along a normal to the surface (see appendix I for proof of law).

21. Law of Refraction

The phenomenon of refraction was known for centuries before the law governing it was discovered. It was first stated by Willebrord Snell in 1621, and put into its present form as a function of sines by the mathematician Descartes. Briefly, the law is:

$$n_a \sin I = n_b \sin I' \qquad (1)$$

where n_a and n_b are constants of the media containing the incident and the refracted rays, respectively, and I and I′ are the angles of incidence and refraction, respectively, both measured from the normal to the ray at the point of incidence.

22. Development of the Law

Let CC′ (fig. 10) be the incident ray, and NN′ the normal at C′. Then, C′C″ is the refracted ray.

Now, $\frac{bB'}{C'C''} = \frac{v_a}{v_b}$ where v_a and v_b are the velocities of light in air and glass, respectively.

But, $\angle bC'B' = \angle CC'N = I$

and $\angle C'B'C'' = \angle C''C'N' = I'$

Therefore:

$$\frac{\sin I}{\sin I'} \quad \frac{bB'/C'B'}{C'C''/C'B'} \quad \frac{bB'}{C'C''} \quad \frac{v_a}{v_b} \quad \frac{n_b}{n_a}$$

If: $n_a = 1/v_a$

$n_b = 1/v_b$

Consequently, the law of refraction, as previously stated:

$$n_a \sin I = n_b \sin I'$$

n is known as the *index of refraction* of the given medium, and it is stated in terms of the velocity of light in free space (vacuum). The velocity of light in free space (symbol c) is 300,000 kilometers per second. Therefore, if its velocity in a certain piece of glass is 200,000 km/sec, this is ⅔c, and the index of refraction of this glass is $\frac{1}{2/3} = \frac{3}{2} = 1.5$.

23. Construction of the Refracted Ray

To construct the refracted ray geometrically, we can proceed as follows:

Let the point of incidence be P (fig. 11) and draw the

normal NN′. Draw AP at the proper angle to represent the incident ray. Lay off on MM′ the distances Pa, Pa′, so that the ratio $\frac{Pa}{Pa'} = \frac{n_2}{n_1}$. In the diagram we have taken the case where n_2 is greater than n_1. Erect a perpendicular from a, meeting

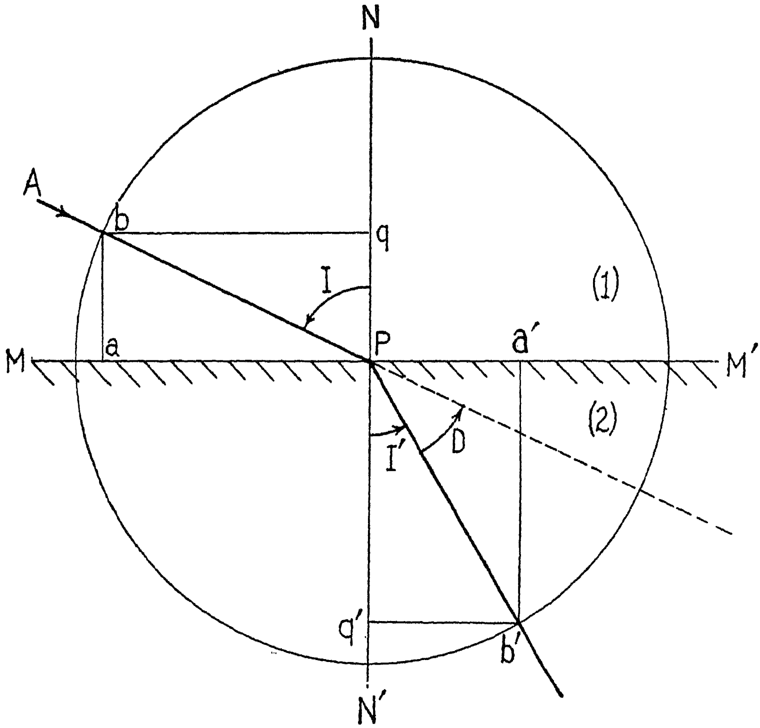

Fig. 11

Construction of the refracted ray

the incident ray at b. Describe a circle around P, of radius Pb. Let a perpendicular fall from a′, meeting the circle around P at b′. Then b′ is a point on the refracted ray, which may then be drawn as the line Pb′ produced.

Proof of the construction: the lines Pb and Pb′ are equal,

and are the hypotenuses of the two triangles Pbq and Pb'q', whose angles at P are the angle of incidence and the angle of refraction, I and I', respectively. Now: $bq = bP \sin I$; $b'q' = b'P \sin I' = bP \sin I'$

But, $bq = aP$

$b'q' = a'P$ and

$\frac{aP}{a'P} = \frac{n_2}{n_1}$. Therefore: $\frac{bq}{b'q'} \quad \frac{n_2}{n_1} \quad \frac{\sin I}{\sin I'}$

24. Deviation of the Refracted Ray

The *angle of deviation* is the angle of the refracted ray with the incident ray produced. It will be seen from the construction in fig. 11, where we have taken the case of light traveling from medium 1 to medium 2 (n_2 is greater than n_1) that the deviation in this case is toward the normal. It is evident (26) that if this case were reversed, that is, if the light were passing from medium 2 to medium 1, the situation would be exactly the reverse, that the length Pa laid out under the incident ray would be shorter than that under the refracted ray, and that, consequently, the ray would be bent *away from the normal.* If we define *optical density* as a measure of the property of slowing down light, so that a medium of large optical density has a large index of refraction, and a medium of low density has a small index of refraction, the light traveling more slowly in the former case than in the latter, we can state the general rule:

In passing obliquely from one optical medium to another, a ray of light will be deviated toward the normal when passing into a medium of greater optical density, and away from the normal when passing into a medium of lesser optical density.

25. Value of the Index of Refraction

The index of refraction measures the optical density of a medium. The optical density has no causal relation with the

physical density (specific gravity) of a substance, although it is usually true that substances with a high specific gravity have a high index of refraction. This is especially true with various types of the same substance, such as glass, which at one time was catalogued by specific gravity in the firm knowledge that the index of refraction would be proportional to it; but there are many cases where a substance of relatively low specific gravity has a high index of refraction, as witness the diamond, which has one of the highest known indices of refraction of any optical medium (2.5).

The index of refraction of a vacuum is, of course, 1.00000; that of air at standard pressure and temperature is 1.0003, so nearly "1" that it is usually taken as unity. These are *absolute* indices of refraction. However, in the case of refraction from one medium to another where neither of the media is a vacuum or air, it is easier to deal with *relative* indices of refraction, which are the ratios of the absolute indices of the media in question, and are given the symbol N. In almost every circumstance, these relative indices (and the absolute indices as well), are found to be between the values ½ and 2.

26. Reversibility of the Light Path

It is also evident from the construction in fig. 11 that, were the incident ray b′P, then the refracted ray would be the ray Pb, since the rules of geometry apply, and the construction holds in either case. Hence we have the principle of the reversibility of the light path. In any case of refraction or reflection of light, the direction of the light can be reversed without any change in the construction. This is a principle of great generality, and of great importance in geometrical optics. It is for this reason, as well as to avoid an unnecessary number of symbols, that we have taken, throughout this book, the symbols I′, U′, m′, etc., as the symbols for the quantities in our equations which refer to conditions *after* reflection or refraction, and have used the symbols I, U, m, etc., as the symbols for the

quantities referring to conditions *before* reflection or refraction. It is clear that if we wished to treat of the light as moving from right to left, it would be necessary only to transpose plain and primed quantities and our equations would hold as written.

CHAPTER IV

Critical Angle

27. Limiting Value of the Angle of Refraction

If we consider a ray of light (fig. 12) incident upon a refracting surface where the optical density of the second medium is greater than that of the first, we find that there is a limiting position for the refracted ray, corresponding to a limiting value of the angle of refraction. For if we take the incident ray in the initial position NP, and rotate it counterclockwise about P as a center, the refracted ray will rotate about P in the same direction, from an initial position on PN′ to a final position PQ, which represents the refracted ray that corresponds to an angle of incidence NPM = 90°.

Thus we may define the angle N′PQ as the greatest value the angle of refraction can attain, and conclude that no light originating outside the surface can ever enter the region bounded by the sides of the angle M′PQ. For any refracted ray not in this region there is a corresponding incident ray, but there is no corresponding incident ray for a refracted ray lying in the region bounded by the sides of the angle M′PQ.

Now, by the principle of the reversibility of the light path (26) we may consider the case of light approaching the surface in fig. 12 in the direction QP, and our construction will be identical. And then for every position of the incident ray in the denser medium there should correspond a position of the refracted ray in the lighter medium. This will be true for any position of the incident ray in the region bounded by the sides of the angle N′PQ, but when the incident ray lies in the region bounded by the sides of the angle M′PQ, there is no

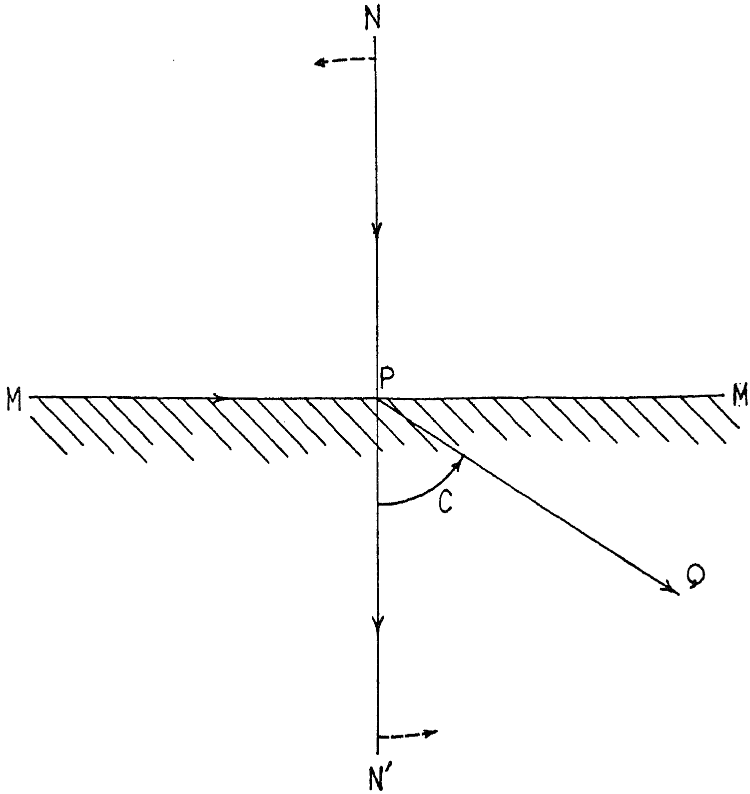

FIG. 12

Critical angle

such corresponding position of a refracted ray in the lighter medium. We must conclude that any ray incident in the region bounded by the sides of the angle M'PQ must be *totally reflected* from the surface. Such reflection, of course, obeys the law of reflection (15).

28. Definition of the Critical Angle

We define the angle N'PQ (= C) as the *critical angle* of the two media involved, the greatest value the angle of incidence

can have if the ray is to pass the boundary, when the incident ray lies in the *denser* medium, and make the following rule:

If, in the case of light incident upon the boundary of a medium of lesser optical density than the medium containing the incident ray, the angle of incidence exceeds the critical angle, the light is totally reflected at the surface.

29. Value of the Critical Angle

The angle N'PQ (critical angle) is the angle of refraction corresponding to the angle of incidence NPM (= 90°), consequently, in the law of refraction:

$$n_a \sin I = n_b \sin I'$$

sin I = 1.00, and I' is the critical angle C, so:

$$\sin C = \frac{n_a}{n_b} = \frac{1}{N} \qquad (2)$$

or, the critical angle is the angle whose sine is the reciprocal of the relative index of refraction of the two media involved (N). The sine of the absolute critical angle is, of course, the reciprocal of the index, for in this case, $n_a = 1.00$.

Thus:

$$\sin C_o = \frac{1}{n_b} \qquad (2a)$$

30. Values of Representative Indices and Critical Angles

A table of the values of the critical angle for common optical media is as follows:

Media	Absolute Index	Velocity of Light	Critical Angle
Air (const. temp. & pres.)	1.0003	186,000 m/s	89°
Water	1.3333	139,500 m/s	49°
Crown glass	1.5275	122,000 m/s	41°
Flint glass	1.6500	113,000 m/s	37°
Diamond	2.5	74,500 m/s	24°

CHAPTER V

Refraction at Plane Surfaces

31. Image of a Point in a Plane Refracting Surface

Given a plane refracting surface MM′ (fig. 13), and a point source s, we see that as we take rays which meet the surface farther and farther from the normal sP, the intersection of the refracted ray with the normal (ray produced) indicated by s'_1, s'_2, etc., moves farther and farther from the surface MM′. Therefore, all the rays from s will not meet in a point after refraction, and consequently there will be no point image formed.

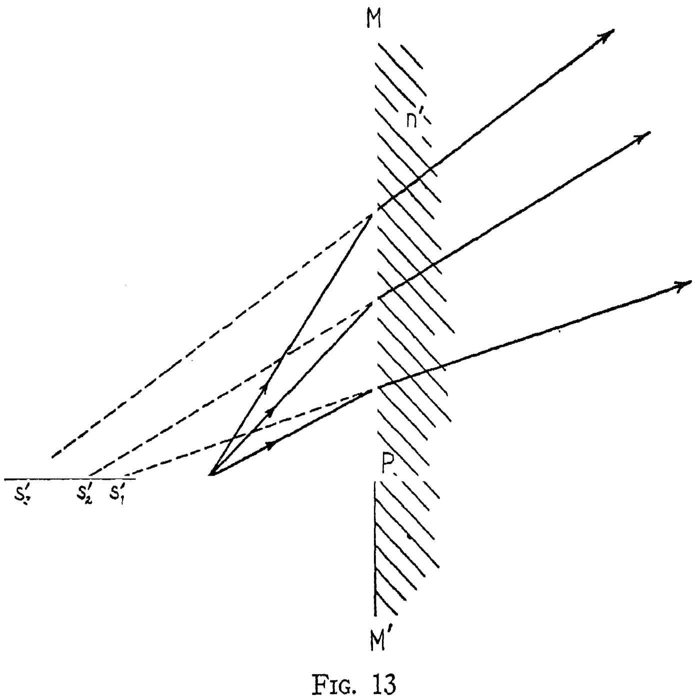

Fig. 13

Refraction at a plane surface

If, however, we confine ourselves to a small bundle in the immediate neighborhood of the perpendicular sP (fig. 14), then for the small angles u involved, sin u = tan u = u, closely enough, if u is measured in radians, and we find that the location of the intersection-point s′ is independent of u. Consequently there is a definite image-point. This can be demonstrated very simply as follows:

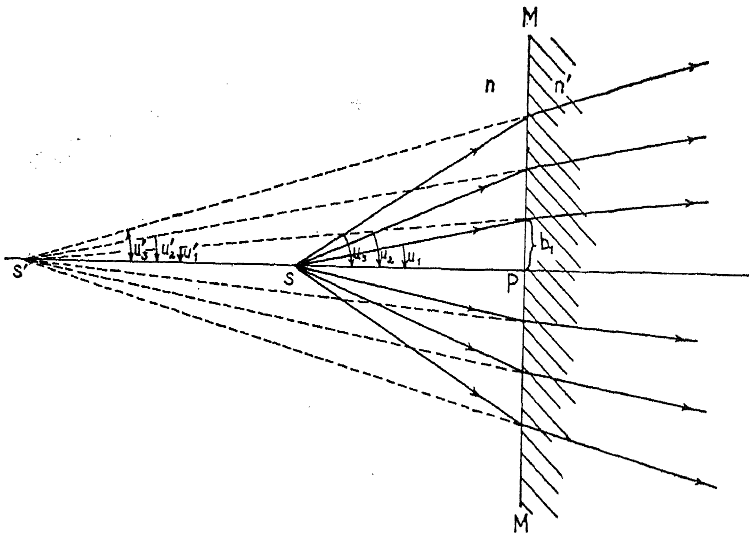

FIG. 14

Paraxial imagery in a plane surface

$$\tan u_1 = u_1 = \frac{}{sP} \qquad \text{(by the law of refraction)}$$

$$u'_1 = \frac{n}{n'} u_1$$

$$s'P = \frac{b_1}{}$$

$$s'P = \frac{b_1}{u_1} \cdot \frac{n'}{n} = \frac{n'}{n} sP \qquad \text{which is independent of u}$$

The shift in position is given by:

$$sP - s'P = \frac{n - n'}{n} sP$$

And, if we use the relative index of refraction by putting $n = 1.00$, and $n' = N$, we have:

$$s'P = N \cdot sP$$

and:

$$sP - s'P = (1 - N)sP$$

Thus we see that for *paraxial* rays, there is an image-point s′ which is displaced from the original object-point s by a distance $(1 - N)sP$ *toward* the refracting surface, where N is the relative index of refraction of the refracting medium to the object medium.

32. The Paraxial Case

Because this consideration of a narrow bundle of rays close to a perpendicular will enter verv frequently into our subsequent work, we shall denote special symbols for conditions pertaining to this idealized situation. The lower-case letters, i, u, m, etc. will be used to indicate the quantities involved in the case of paraxial conditions, and the upper-case letters, I, U, M, etc. will be used to denote the quantities involved in the case of "finite" aperture (where the rays are not limited to the region immediately adjacent to the axis). The condition of the paraxial case is merely that the angles of incidence, refraction, and convergence be sufficiently small that we can express their sines and tangents by the radian values of the angles themselves without sensible error, and their cosines as equal to unity. The paraxial conditions always yield simpler formulae than the actual cases of finite aperture, and hence lead to very valuable

approximate results. Furthermore, the majority of actual optical systems realize the paraxial case very closely.

We may frequently draw diagrams (such as fig. 22) where the angles i and i′ are indicated with paraxial symbols but are not of paraxial dimensions. This exaggeration is merely for the purpose of clarity in the figure, and it should be remembered that if the rays are to be considered paraxial, i and i′ as well as h, must be very small (less than 1°) and the rays clustered about the pole A.

We are familiar with the distorted appearance of objects seen under water, and can now see from the discussion in (31) that this is due to the fact that the imagery is not strictly paraxial, but the aperture of the eye is sufficiently small for the paraxial condition to be partially fulfilled, and a blurred, distorted image results.

33. Refraction by a Plane-Parallel Plate

If we investigate the effect of a plane-parallel plate (a plate whose two sides are plane and parallel) on rays emanating from a point source, s, we find that all the rays emerge along paths which are parallel to their original paths of incidence.

This is easily proved. For if the angle N′PP′ (fig. 15) is the angle of refraction at the first surface, then, since NN′ is parallel to N'_1N_1, angle $N'_1P'P$ is equal to angle N′PP′. But angle $N'_1P'P$ is the angle of incidence at the second surface. Therefore, at the second surface we have exactly the reverse condition from that at the first surface and the conditions are identical except that the direction of the ray is reversed, and, by the principle of the reversibility of the light path (26), the angle of refraction at the second surface will be equal to the angle of incidence at the first surface, and the ray will emerge parallel to its original path of incidence.

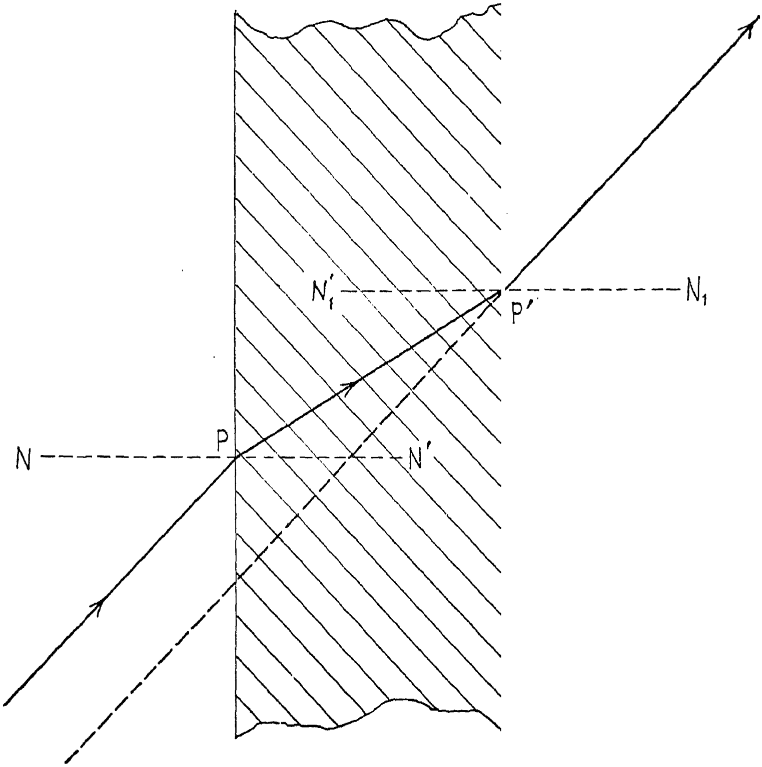

FIG. 15

Refraction through a plane-parallel plate

34. Apparent Direction of a Point Observed Through a Plane-Parallel Plate

If an object is observed through a plane-parallel plate, all the rays entering the eye from the object are displaced laterally except those exactly normal to the plate. Thus, unless an object is infinitely distant, it will be shifted in apparent position. This shift will be *toward* the plate, when measured along the perpendicular to the plate.

35. Paraxial Imagery in a Plane-Parallel Plate

Since a plane-parallel plate represents two plane refracting surfaces, there will be paraxial imagery of the same nature as described in (31). If n is the index of refraction of the object medium, and n′ that of the plate, then the shift in position of the object will be given by (fig. 16, appendix I):

$$ss'' = d\left(\frac{n' - n}{n'}\right)$$

or, using the relative index of refraction:

$$ss'' = d\left(\frac{N-1}{N}\right) \qquad (3)$$

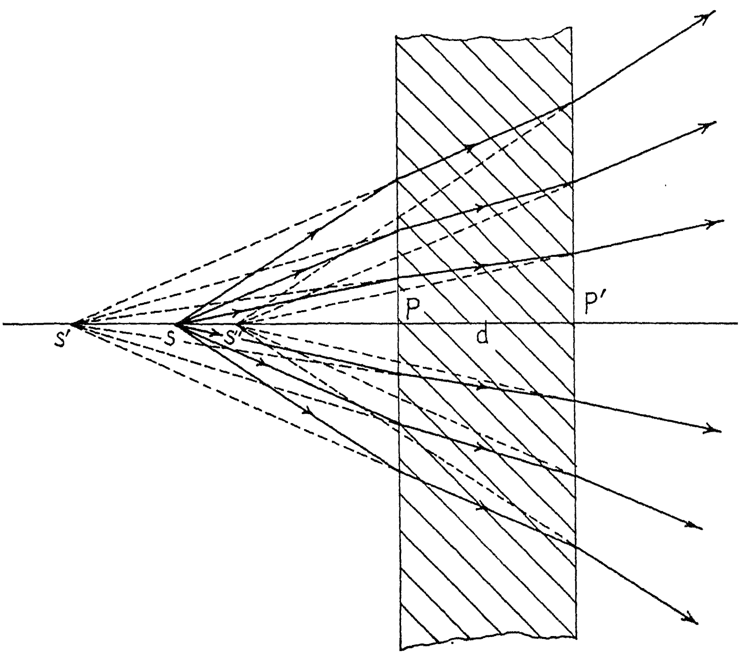

FIG. 16

Paraxial imagery in a plane-parallel plate

Thus we see that the shift in position of the object depend only upon the thickness and the index of refraction of th plate, and not at all upon the distance of the object or the eye For glass of index 1.5, the shift will be equal to one-third th thickness of the plate.

CHAPTER VI

REFRACTION THROUGH A PRISM

36. Definition of a Prism

To be perfectly general, the term prism may be applied to any sort of solid refracting element whose sides are plane. There have been many attempts at a rigorous definition of a prism, but it is usually possible to find some optical element which is not included in the definition although still considered a prism, so that it is better to make the definition sufficiently broad to cover all cases.

For the purpose of this chapter we shall consider a prism the optical medium comprised between two plane surfaces not parallel to each other, which is merely a case of generalizing the conditions of the plane-parallel plate.

The acute angle between the two faces of the prism is the vertex, or *refracting angle* of the prism, A (fig. 17). The edge formed by the intersection of these two faces is called the refracting edge of the prism.

The deviation of the ray by the prism is drawn as the angle D and it can be shown (appendix I) that the following rules hold:

1. The deviation of the ray will always be *away from the refracting edge.*
2. The ray which will be *least* deviated by the prism is that ray which *traverses the prism symmetrically;* that is, (39) the case where the final angle of emergence is equal to the initial angle of incidence and where the path of the ray through the prism is perpendicular to the bisector of the refracting angle (fig. 18).

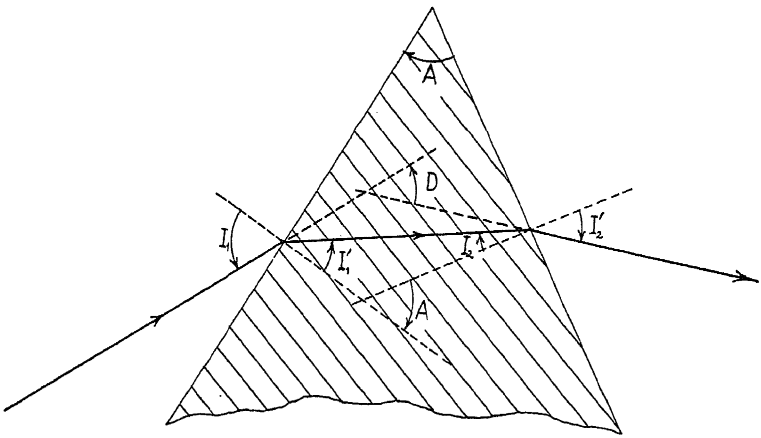

FIG. 17

Refraction through a prism

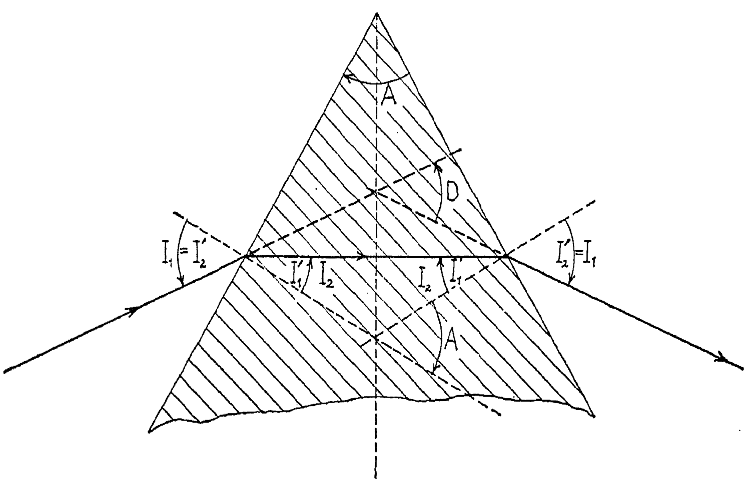

FIG. 18

The symmetrical ray; minimum deviation

37. Total Reflection at the Second Face of a Prism

If the angle I_2 (fig. 17) is greater than C, the critical angle of the two media involved, then the ray will be totally reflected at the second face of the prism (fig. 19), as shown in chapter IV.

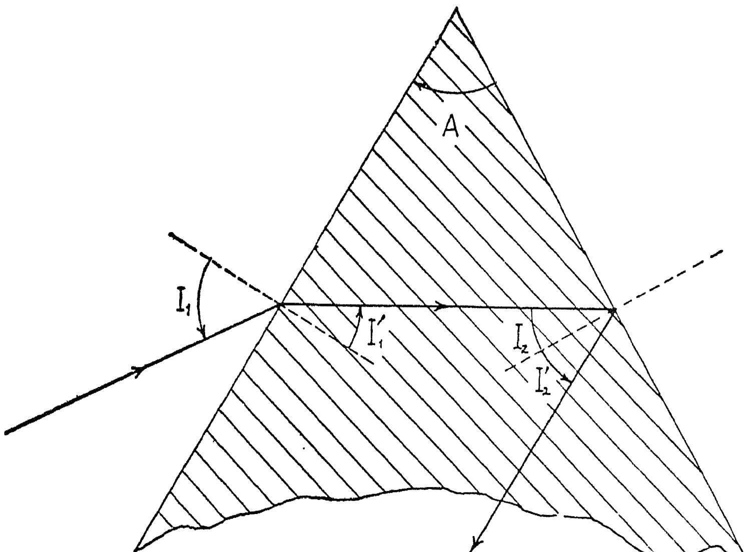

FIG. 19

Total reflection at the second face of a prism

There is, therefore, a limiting value of the initial angle of incidence I_1 corresponding to a ray which will emerge from the second face of the prism at $I'_2 = 90°$, such that any rays entering the first face of the prism at an angle less than this limiting angle will be totally reflected at the second face. If the refracting edge is taken at the top of the diagram as in fig. 19, the light entering from the left, and the angle of incidence measured according to the usual sign conventions (41), it will

follow that all angles of incidence less (algebraically) than the limiting value will correspond to rays which will be totally reflected at the second face of the prism.

The value of this limiting angle (appendix I) is given by:

$$\sin I_0 = \frac{n'}{n} \sin(A - C) \tag{4}$$

where I_0 is the limiting angle of incidence, A the refracting angle of the prism, and C the critical angle of the two media involved, n and n', of course, having their usual significance. Using the relative index by putting $n = 1.00$, $n' = N$, and expressing C in terms of N by equation (2), we can write

$$\sin I_0 = \sin A \sqrt{N^2 - 1} - \cos A \tag{4a}$$

This principle of total reflection is of very general application in instruments where it is required to change the direction of the optical axis, and in many types of erecting systems. Applications of this important principle will be discussed at some length in chapters X and XIV.

38. Special Cases of Refraction at the Second Face of a Prism

A consideration of the relationship between the initial angle of incidence I_1, the final angle of emergence I'_2, and the refracting angle A, discloses certain significant cases:

1. If A is greater than 2C, where C is the critical angle of the two media involved, then $\sin I_0$ is greater than 1; therefore, such a prism will not transmit any ray through the two faces.
2. If A is equal to 2C, then $I_0 = 90°$; the only ray which can pass through both faces of the prism is the one grazing the surface at both incidence and emergence. This is a case of purely theoretical interest, since in a practical case of this sort, the loss of light by external reflection at the incident face would be 100%.

3. If A is greater than C, but less than 2C, then I_o lies between 0 and 90°; the limiting position of the incident ray is on the side of the normal away from the refracting edge.
4. If A is equal to C, then $I_o = 0$; the limiting position is perpendicular to the incident face, and all rays lying on the side of the normal toward the refracting edge will be totally reflected, while those on the opposite side of the normal will be refracted through the prism.
5. If A is less than C, I_o is negative; the limiting position of the incident ray lies on the side of the normal toward the refracting edge.

These five cases are illustrated in fig. 20.

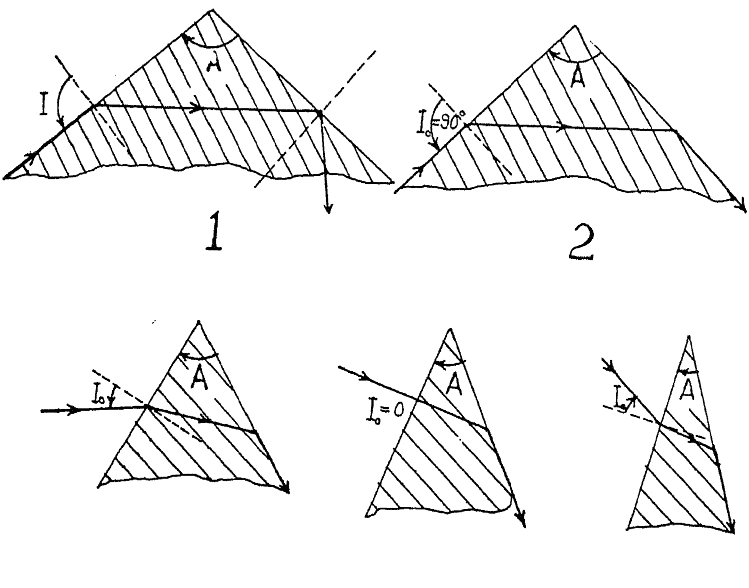

FIG. 20

Significant values of limiting angle of incidence

1. A greater than 2C. 2. A equal to 2C. 3. A greater than C but less than 2C. 4. A equal to C. 5. A less than C.

39. Minimum Deviation

The ray (appendix I) through the prism for which the deviation will be the least is that ray which is symmetrical; the ray whose path inside the prism is perpendicular to the bisector of the refracting angle. The amount of the deviation in this special case is

$$D_o = 2I_1 - A \qquad (5)$$

where, also, $I'_1 = I_2 = \dfrac{A}{2}$

40. Deviation of a Thin Prism

If the refracting angle is small, then the radian values of the angles may be substituted for their sines, and since the deviation of a thin prism is not very different for any ray than for a symmetrical ray, the deviation of a thin prism can be written as:

$$d_0 = (N - 1)\,A \qquad (6)$$

(appendix I)

CHAPTER VII

Reflection and Refraction at a Spherical Surface

41. Definitions

The center of the spherical reflecting or refracting surface ZZ′ (fig. 21) is denoted by C. The line XX′ through the center and a point on the surface A, is the *principal axis*, and since all lines through C will have the same properties as XX′, the principal axis will usually be determined by external conditions, such as other succeeding or preceding surfaces. The point A is called the *pole*. The point of contact of an incident ray with the surface is P, and the point of intersection of this incident ray (produced if necessary) with the principal axis is B. The line through P and C is the normal NN′, upon which $r = PC$ is the radius of curvature of the surface. The height of P above the principal axis is denoted by h. The angle made by the incident ray with the normal is I, and the angle made by the incident ray with the principal axis is U, the *angle of convergence*.

We must also make certain conventions as to the signs of the quantities involved, in order to make the relationships general and applicable to all cases. Thus we make the convention that all distances falling to the right of the surface shall be positive and those falling to the left shall be negative. The angles of incidence and convergence, I and U, shall be positive if counterclockwise and negative if clockwise; angle I shall be measured *from the normal to the ray*, and angle U shall be measured *from the ray to the axis*. A word of caution at this point about signs: the signs of quantities in optical calculations are extremely important, as they frequently denote significant facts about the results. Moreover, in optical calculations particularly, signs

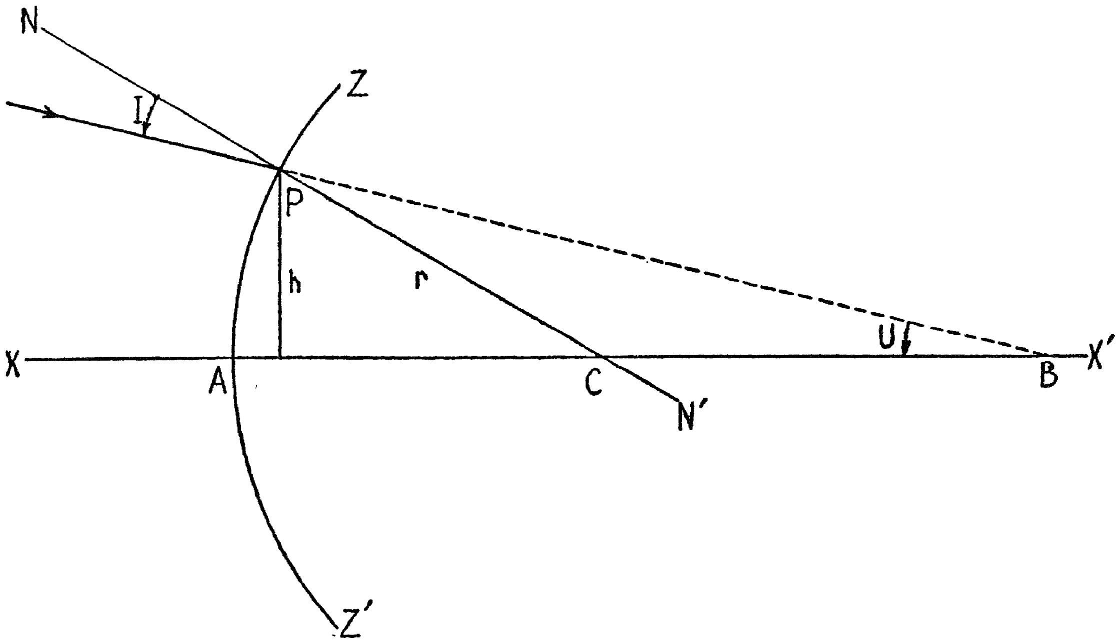

FIG. 21

Definitions for reflection or refraction at a spherical surface

are a never-ending source of difficulty and should be vigilantly watched at all times. A scale drawing is always helpful in keeping the conditions clearly in mind.

42. Restriction to Paraxial Rays

For this chapter, we shall confine ourselves to *paraxial* rays, as defined in (32); that is, to rays which are incident upon the surface in the immediate neighborhood of the pole A, and at such angles of incidence and convergence that we may put the sines and tangents of these angles equal to the radian values of the angles themselves. By making this restriction, we can work out important relationships in simplified form. In this case, the quantities shown in fig. 21 will be indicated by lower-case symbols, according to our convention in (32).

43. Reflection at a Spherical Surface

We expand our sign and symbol conventions to include the data of the reflected ray, and establish symbols for the various quantities involved (fig. 22). The angle of reflection is the angle between the normal and the reflected ray, and is denoted by I′. It is measured *from the normal to the ray,* as is I. The angle of convergence of the reflected ray (produced if necessary) with the principal axis, U′, is measured *from the ray to the axis,* as is U. Both angles have the same sign conventions as I and U; they are counted positive if the rotation is counterclockwise.

We designate the distance $AB = m$; and the distance AB', from the pole to the intersection B′ of the reflected ray with the axis, as $AB' = m'$.

44. Paraxial Imagery by a Spherical Reflecting Surface

It can be shown (appendix I) that when we restrict ourselves to paraxial rays, the following relationships will hold between the quantities involved in fig. 22:

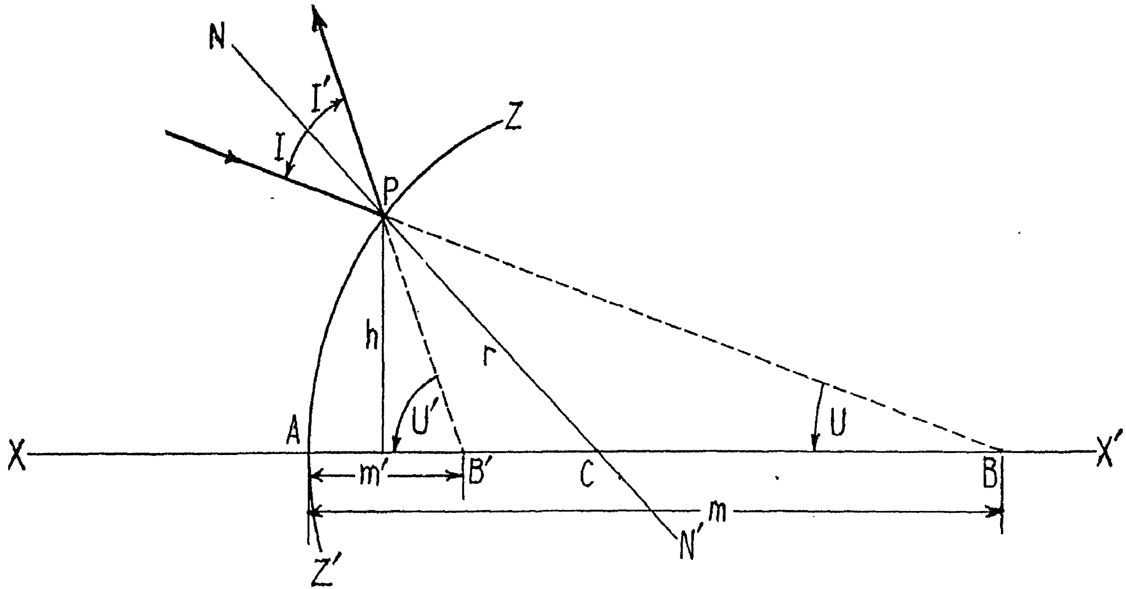

Fig. 22

Reflection at a spherical surface

$$i' = -i$$

$$i = \frac{(m - r)\,u}{}$$

$$u' = u + i - i' = u + 2i$$

$$m' = \frac{ri'}{u'} + r$$

If we substitute, in the equation for m′, the values given for the unknown quantities in terms of the known quantities m, r, and u, we obtain:

$$m' = \frac{rm}{2m - r}$$

which may be written:

$$\frac{1}{m'} + \frac{1}{m} = \frac{2}{r} \qquad (7)$$

The significance of this equation is that the angle u does not appear. This means that the position of m′ is dependent only upon the distance m and the radius of curvature r, of the surface. Consequently, if a point source of light is located on the principal axis in front of a spherical reflecting surface, then the surface will form a point image of this source, and the relation of the distances of source and image will be as stated in equation (7). We must remember that this is true only for paraxial rays.

45. Focal Length of a Spherical Reflecting Surface

If the point source of light mentioned in the preceding paragraph is located at a very great distance (strictly speaking, at infinity) then $m = \infty$, $\frac{1}{m} = 0$, and we have:

$$m'_o = \qquad (8)$$

This is the case of *parallel light.* When an object is located at a great distance, then the separate rays from a given point on that object will diverge at such small angles that for all practical purposes they are parallel, and the wave fronts are plane surfaces. In most practical cases, a distance of from 50 to 100 times the focal length may be considered to be reasonably infinite.

The point m'_0, located at a distance from the reflecting surface equal to half its radius, and on the same side of the surface as its center, has a special significance. It is called the *principal focus,* and is denoted by F. It is the point where the image of an infinitely distant object-point is formed. The distance from the pole to F (m'_0) is the *focal length,* and is denoted by f. It can be seen from equation (8) that if the reflecting surface is convex to the incident light, r will be positive, and also f; whereas, if the reflecting surface is concave to the incident light, r and f will be negative. From this we conclude that a convex mirror has a positive focal length, and a concave mirror a negative focal length.

46. Real and Virtual Images in a Spherical Reflecting Surface

It is obvious that the light will always stay to the left of a reflecting surface (when it is incident from the left), so if the image is formed at the right it will be virtual (11). We can see from equation (7) that the image will be real for a concave mirror unless m is negative and numerically less than f, in which case it will be virtual. Also, for a convex mirror, the image will be virtual unless m is positive* and less than f, in which case the image will be real. The conditions for real and virtual imagery in both concave and convex reflecting surfaces are illustrated in fig. 23.

* If m is positive, the object is a *virtual* object; that is, the rays are converging to a point to the right of the surface, and thus will never actually reach this point. Such virtual objects could, of course, only exist in reality by reason of their being real images formed by some other optical element.

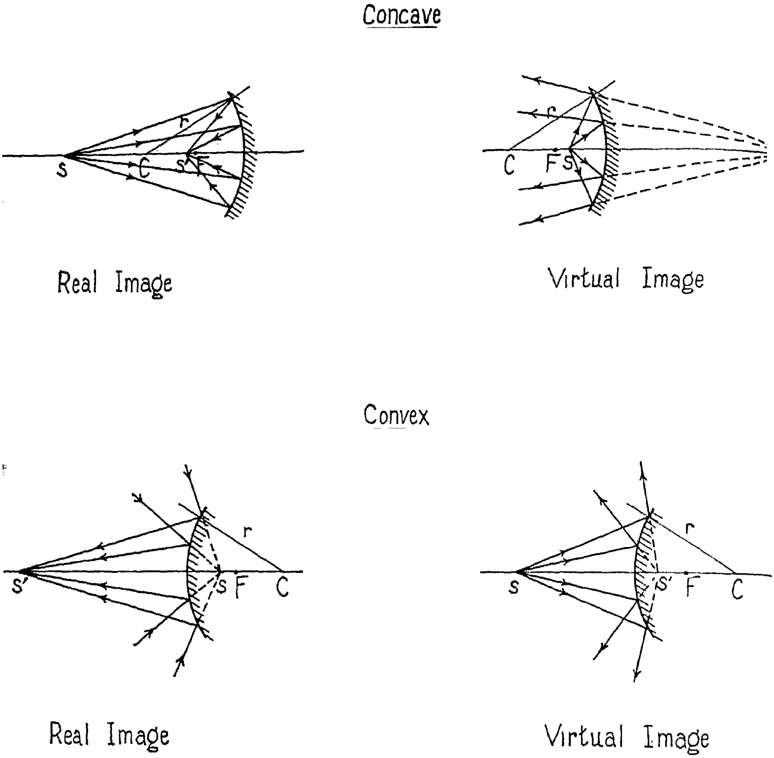

FIG. 23

Real and virtual images in a spherical reflecting surface

47. Refraction at a Spherical Surface

For a refracting surface, we have the same sign and symbol conventions as detailed in (41) and (43), with the addition of n and n′, the indices of refraction of the medium to the left and to the right of the surface, respectively. We need only make one additional definition for simplification, namely that a surface which is convex to the lighter medium be called a convex surface, and a surface which is convex to the denser medium be called a concave surface (fig. 24).

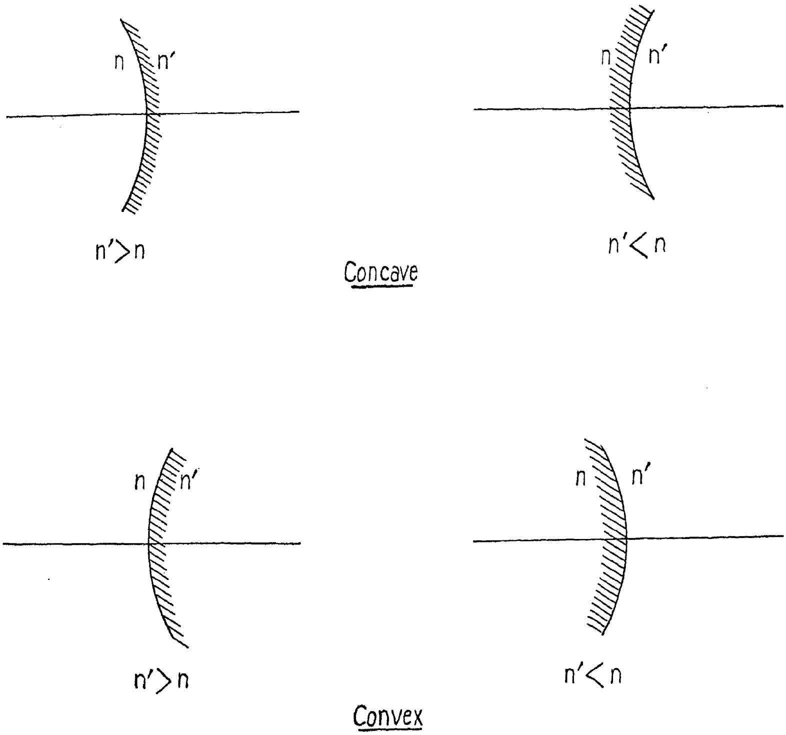

FIG. 24

Concave and convex refracting surfaces

48. Paraxial Imagery by a Spherical Refracting Surface

It can be shown (appendix I) that when we restrict ourselves to paraxial rays, the following relationships will hold between the quantities involved in fig. 25:

$$ni = n'i'$$

$$i = \frac{(m - r)u}{r}$$

$$u' = u + i - i'$$

$$m' = \frac{ri'}{u'} + r$$

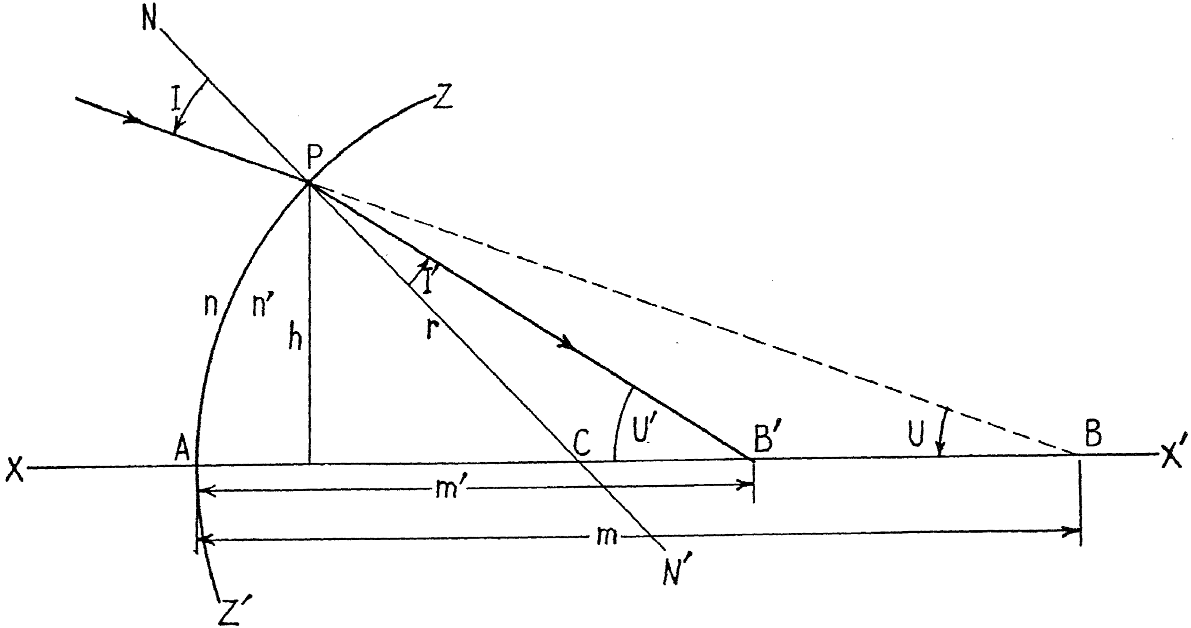

FIG. 25

Refraction at a spherical surface

Now if we substitute, in the equation for m′, the values given for the unknown quantities in terms of the known quantities m, r, n, n′, and u, we obtain

$$m' = \frac{rn'm}{(n'-n)m + nr}$$

which may be written

$$\frac{n'}{m'} - \frac{n}{m} = \frac{n'-n}{r} \qquad (9)$$

The individual relationships are the same as for reflection (44), except for the relation between i and i′, which is the law of *refraction* (21). Equation (9) is of the same form as equation (7), and is also independent of the angle u. Consequently, if a point source of light is located on the principal axis of a spherical refracting surface, then the surface will form a point image of this source, and the relation of the distances of source and image will be as stated in equation (9). We must remember that this is true only for paraxial rays.

49. Focal Lengths of a Spherical Refracting Surface

If the point source of light mentioned in the preceding paragraph is located at a very great distance (infinity), then $m = \infty$; $\frac{n}{m} = 0$, and we have

$$m'_0 = \frac{n'r}{\ } \qquad (10)$$

The point represented by m'_0 has a special significance. It is called the *principal focus,* and is denoted by F′. This symbol must be primed according to our definition in (26). It is the point where the image of an infinitely distant object is formed. The distance from the pole to F′ (m'_0) is the *focal length,* and is denoted by f′. If the refracting surface is convex,

according to our definition in (47), either n′ will be greater than n and r positive, or n′ will be less than n and r negative. In either case, it will be seen from equation (10), m'_o will be positive. Conversely, if the surface is concave, m'_o will be negative.

The derivations from the equation for a refracting surface, therefore, are almost identical with the derivations for the reflecting surface in (45) except that the signs of the focal length are reversed for a given type of effect upon light (converging or diverging). The signs are consistent for the type of surface, however (convex or concave). The indices of refraction, of course, are involved in the expression for the focal length of a refracting surface.

However, this is only half the story of a refracting surface. Since the light actually passes through a refracting surface, we may consider the light as incident from either the right or the left (light incident from the right would be meaningless for a reflecting surface in the position we have drawn it). For light incident from the left (a universal conception in geometrical optics), n is associated with m and with i, while for light incident from the right, n is associated with m′ and i′. Hence for light incident from the right, we have, in the place of equation (9):

$$\begin{array}{ccc} n & n' & n - n' \\ m' & m & \end{array} \tag{9a}$$

and, in place of equation (10):

$$\begin{array}{cc} & nr \\ m'_0 = & \end{array} \tag{10a}$$

and the two values for m'_o in equations (10) and (10a) will be different. Hence, we see that there are *two* focal points and *two* focal lengths for a spherical refracting surface. If we call the principal focal length for light incident from the left f′, and

that for light incident from the right f, we have, from (10) and (10a):

$$f' = \frac{n'r}{n' - n}$$

$$f = \frac{nr}{n - n'}$$

and we can exhibit the relationship between f and f′ by:

$$\frac{n'}{f'} = \frac{n' - n}{r} = -\frac{n}{f} \qquad (11)$$

whence we see that f and f′ are always opposite in sign, and that their ratio is:

$$\frac{f'}{f} = -\frac{n'}{n} \qquad (11a)$$

50. Real and Virtual Images in a Spherical Refracting Surface

It is evident that the light will always pass through the refracting surface, consequently (considering the light as incident from the left) if the image is formed on the right (m′ positive) it will be real, and if it is formed at the left (m′ negative) it will be virtual. We can see from equation (9) that the image will be real for a convex refracting surface unless m is negative and numerically less than f, in which case it will be virtual, and that for a concave refracting surface, the image will be virtual unless m is positive and less than f′, in which case it will be real. The conditions for real and virtual imagery in both convex and concave refracting surfaces are illustrated in fig. 26.

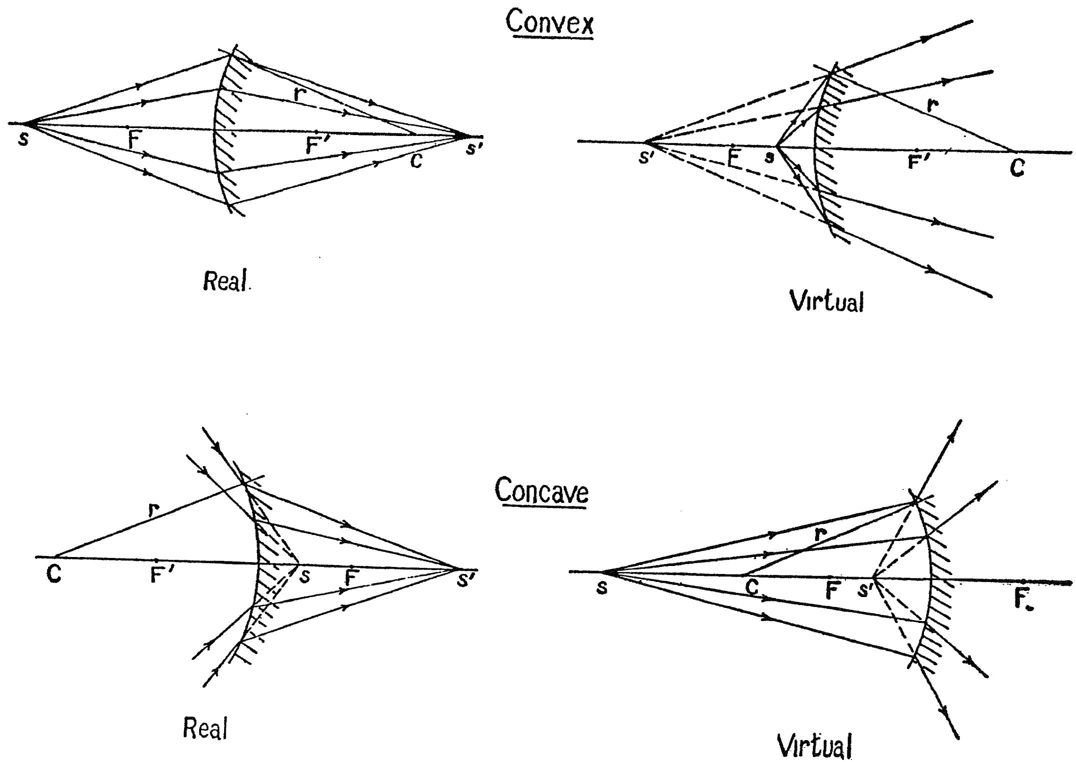

FIG. 26

Real and virtual images in a spherical refracting surface

51. Reflection as a Special Case of Refraction

If we examine equation (9) we see that by putting n' equal to $-n$, we obtain equation (7), which indicates that we can treat reflection as a special case of refraction by making this substitution. If we do this, equation (11) becomes an identity, and f and f' are seen to be coincident for a reflecting surface. In the calculation of optical systems containing both reflecting and refracting surfaces, it is of considerable advantage to be able to treat all surfaces in the same manner and with the same equations.

52. Movement of Object and Image

From equations (7) and (9) we can draw curves showing movement of the image corresponding to a movement of the object. Equation (7) is an equilateral hyperbola with center at (f,f), there being two cases, according to f being positive or negative. On either branch, as m approaches f, m' approaches infinity, and vice versa. One branch passes through $(0,0)$, corresponding to the condition when object and image coincide at the pole of the surface. Equation (9) is also an equilateral hyperbola, with centers at (f,f'), there also being two cases, according to the sign of f'. As m approaches f, m' approaches infinity, and as m' approaches f', m approaches infinity. For the refracting surface also, one branch passes through $(0,0)$, corresponding to the condition when object and image coincide at the pole of the surface. The curves are illustrated in figs. 27 and 28. It will be noted that, for a reflecting surface, the image and object travel in opposite directions, while for a refracting surface, they both travel in the same direction.

53. Extra-Axial Object-Points

If the spherical reflecting or refracting surface ZZ' (fig. 29) is rotated through a very small angle about its center, C, then

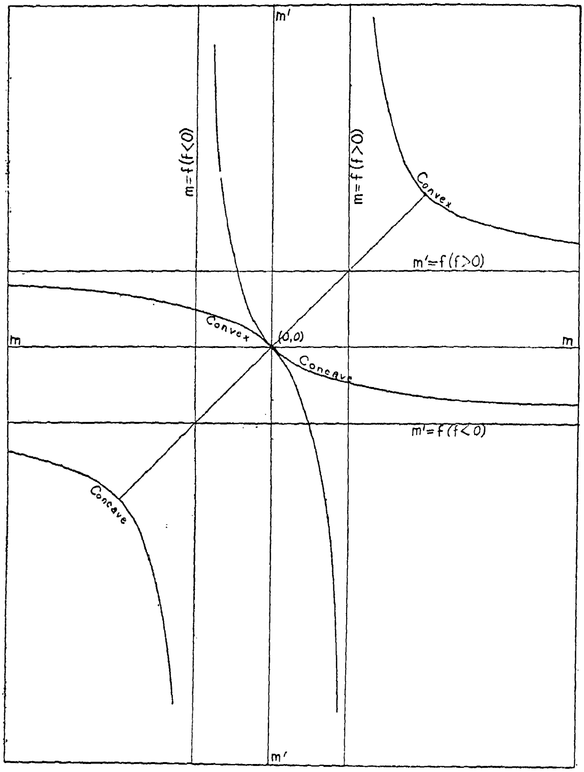

FIG. 27

Image curves for a spherical reflecting surface

b and b′ will undergo a slight displacement to q and q′. It is evident that the same relation, expressed by equations (7) and (9), will hold between q and q′ as holds between b and b′, since the surface is symmetrical about any line drawn through its center. Also, if the angle of rotation is very small, and if the line bq is perpendicular to the principal axis XX′, then the line b′q′ may, with negligible error, be considered perpendicular to the principal axis. Thus we can conclude that, *for the paraxial case,* the image of a plane object perpendicular

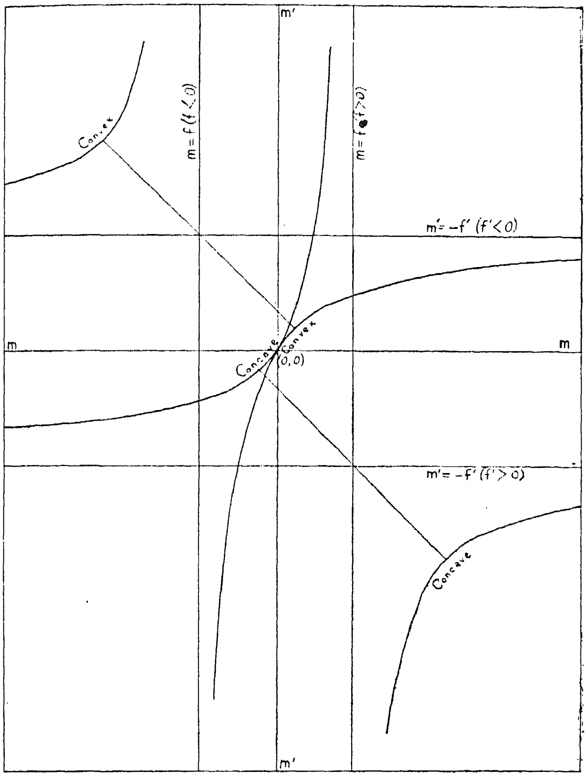

FIG. 28

Image curves for a spherical refracting surface

to the principal axis will also be a plane perpendicular to the axis.

54. Linear Magnification

The ratio between bq and b'q' (fig. 29) is known as the linear or lateral magnification. It can be shown (appendix I) that the linear magnification is given by:

$$M = \frac{b'q'}{bq} = -\frac{m'}{m} \qquad (12)$$

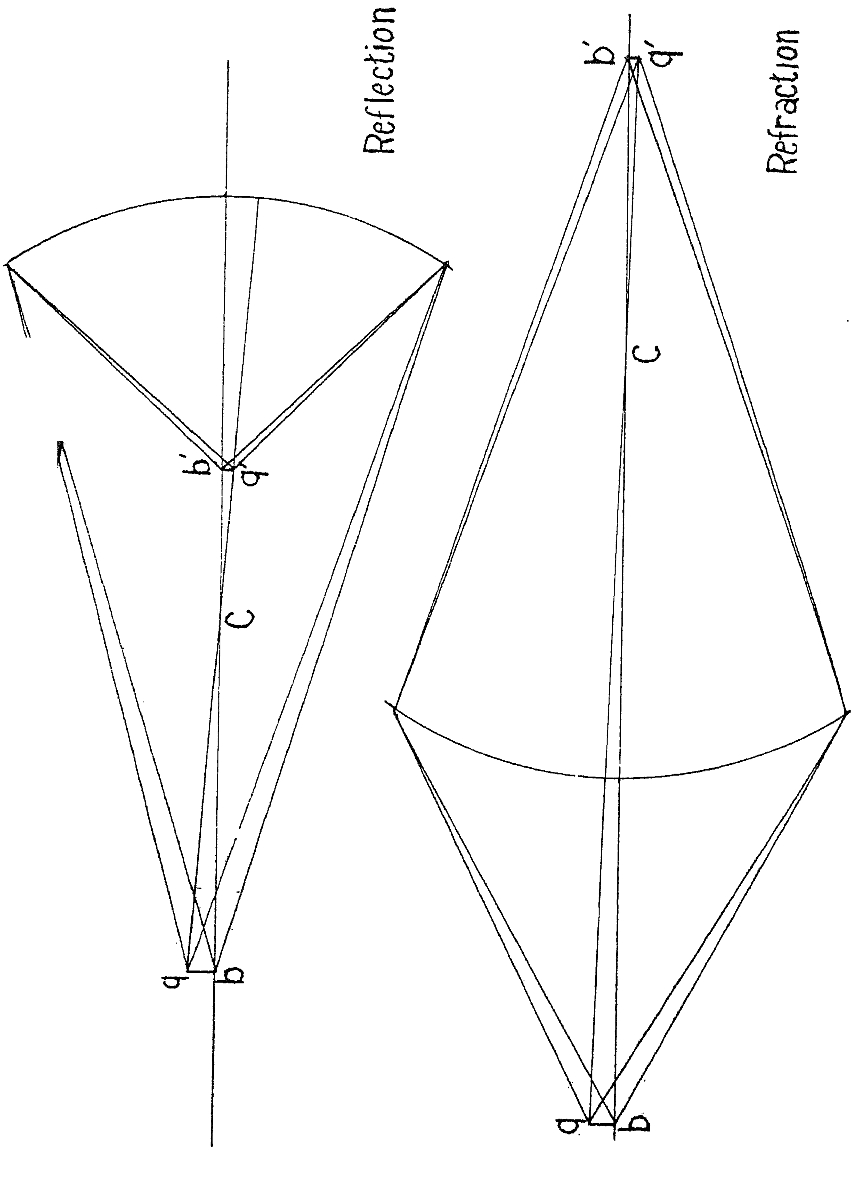

Fig. 29

for a reflecting surface, and by:

$$M = \frac{b'q'}{bq} = \frac{n}{n'} \cdot \frac{m'}{m} \tag{13}$$

for a refracting surface, and the image will be erect or inverted according as the value of M is positive or negative.

55. Theorem of Lagrange

The above result may be stated in a form known as the theorem of Lagrange, although sometimes referred to as the Smith-Helmholtz law. Since we are dealing with paraxial rays and since the height, h, of the ray at the point of meeting the surface is the same for both rays, incident and reflected or refracted, the convergence angles, u and u′, will be inversely proportional to the distances m and m′. That is:

$$m'$$

$$m$$

Making this substitution in equation (13) and cross-multiplying, we obtain:

$$n'\,y'\,u' = n\,y\,u \tag{13a}$$

where $y = bq$
$y' = b'q'$

In the case of a reflecting surface n and n′ disappear and the two terms are opposite in sign for our conventions. This is a very general relation and holds not only for a single surface but for any number of surfaces in a centered optical system.

CHAPTER VIII

THIN LENSES

56. Definitions

We define a lens as a limited portion of an optical medium bounded by two spherical surfaces (the plane being considered as a special case of a sphere, where the radius is infinite). Lenses with other than spherical surfaces are discussed briefly in (70). It is evident that in the case of light passing through a lens, we have two cases of refraction, one at the entering surface and one at the emerging surface. The principal axis is defined as the line which passes through both centers of curvature, and is, therefore, normal to both faces (surfaces) of the lens.

57. Types of Lenses

Since, by the above definition, a lens is perfectly symmetrical about the principal axis, it may be represented by a plane section in which the two faces are the arcs of two circles, one about each center of curvature. These two arcs will intersect at two points equidistant from the principal axis or they will not intersect at all, thus giving rise to two general classes of lenses.

If the two arcs intersect, we have three possible cases, illustrated in fig. 30a. They may intersect in such a way as to make both faces convex by our definition in (47), or so as to make one surface convex and the other concave. In the latter case, the concave surface will always be the surface of longest radius. A special case is where one surface is a plane. These three types are known as double-convex, meniscus, and plano-convex, respectively.

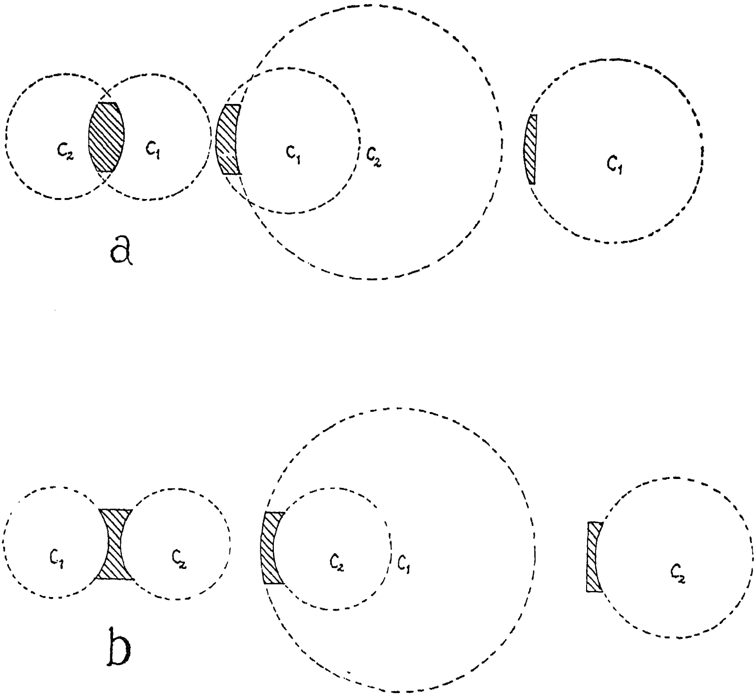

FIG. 30

Types of lenses

a. Converging lenses; b. Diverging lenses.

If the two arcs do not intersect, we have the double-concave, a meniscus form, where the concave surface has the shortest radius of the two, and a plano-concave form. These are illustrated in fig. 30b.

If we define the *curvature* of a surface as the reciprocal of the radius (in accordance with common geometrical concepts), and define the curvature of a *lens* as the *difference* of curvatures of its two surfaces, and if we further adopt the sign conventions of the radii given in (41), we find that the curvatures of all the lenses in the first class are positive, and of all

those in the second class, negative. We shall anticipate a little and state that a positive curvature means a positive focal length, and that a positive focal length means that the lens will *converge* light; also, that a negative focal length means that the lens will *diverge* light, and thus arrive at our designations of the two general classes of lenses as *converging* and *diverging*. Many writers refer to these two classes of lenses as convex and concave, repectively, but this is insufficiently rigorous, and it does not properly describe the meniscus form of either class. The terms convex and concave should be reserved for application to the *surfaces* of a lens, and not be applied to the lens as a whole. These two classes of lenses are frequently referred to as positive and negative lenses, which is perhaps an even better terminology, mathematically speaking, but less descriptive.

When the curvatures of the two surfaces are equal in value but opposite in sign, the lens may be called a *symmetric* lens. This will be either double-convex or double-concave. A special case of this is a solid sphere. If the centers of curvature of the two surfaces are coincident, we have a *concentric* lens. This may be either double-convex (of which the solid sphere is again a special case) or a meniscus form for which the radial thickness is a constant. This latter form has been used to increase the effective field of view of telescopes and in this connection has attained the unfortunate name of plano-meniscus, a meaningless term.

It is to be noted that the distinguishing feature of a converging lens is that it is thicker at the center than at the edge, and conversely, a diverging lens is thicker at the edge than at the center.*

The classification of lenses into converging and diverging omits the transition type, the *lens of zero curvature*. This is a lens whose thickness along the principal axis is equal to the

* Note that this thickness must be measured parallel to the principal axis and not radially.

distance between the centers of curvature, both radii having the same sign. It is obvious that for this type the radii will be equal in value and direction, and the curvature of the entire lens will be zero.

58. Optical Center of a Lens

When a ray of light passes through a lens, it will be subjected to two refractions, one at each surface, with the single exception of the ray which is coincident with the principal axis. This ray will pass through undeviated because it strikes both surfaces normally.

Now when, upon refraction at the second face of a lens, a ray emerges along a path which is parallel to its original path of incidence, the path of this ray inside the lens crosses the principal axis in a remarkable point, known as the *optical center* of the lens. This point is characterized by the fact that any ray passing through it will emerge parallel to its path of incidence. This can be shown by drawing two parallel radii, C_1P_1 and C_2P_2 (fig. 31a). Since the tangents to the surfaces at P_1 and P_2 are perpendicular to their respective radii, they are parallel to each other and consequently the effect on the ray entering at P_1 and emerging at P_2 will be exactly that of a plane-parallel plate, which was discussed in (33). It can be shown (appendix I) that for any point P_1 there is an incident ray which will emerge at the point P_2 parallel to its original path of incidence, and that the sum total of these rays from all points P_1 will intersect the principal axis at the optical center, 0; in other words, that the position of the point 0 depends only upon the geometrical structure of the lens, and not upon the rays which pass through it.

Since the ray which is coincident with the principal axis is one of the rays which emerges parallel to its original path, it is evident from this consideration alone that the optical center will lie upon the principal axis.

The optical center of a lens is not necessary within the lens,

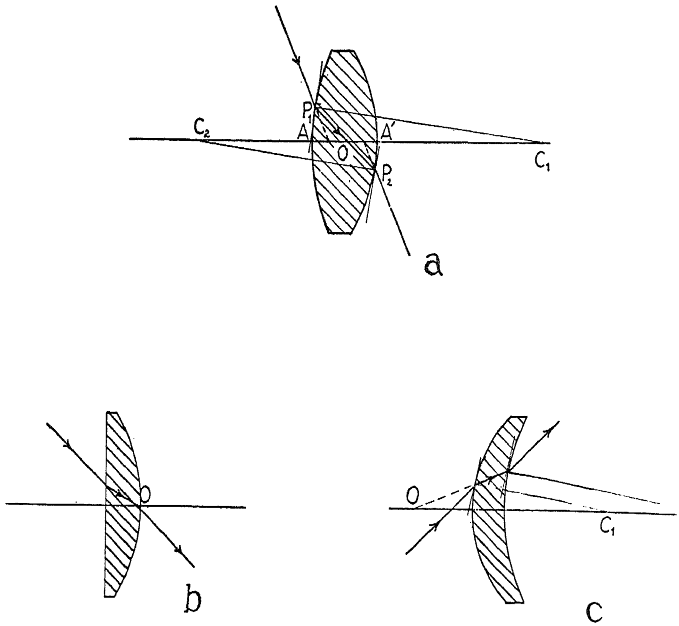

FIG. 31

Optical centers of lenses

although it represents the intersection of the path of the ray within the lens with the principal axis. In a meniscus lens of either class, the optical center lies entirely outside the lens, as shown in fig. 31c, and in the case of either a plano-convex or a plano-concave lens, the optical center lies at the pole of the spherical surface, as illustrated in fig. 31b.

59. Definition of a Thin Lens

In order to develop simplified formulae for the formation of images by lenses, we shall at first confine ourselves to so-called "thin" lenses. A thin lens is a lens considered to be infinitely thin, so that its thickness can be neglected in the formulae, thus simplifying them to a considerable degree. In practical work,

the "thin-lens" equations are surprisingly accurate, especially for lenses which are actually thin with respect to the other dimensions, such as diameter and radii. The importance of the thickness of a lens becomes noticeable when we deal with the aberrations of lenses, a subject to be covered in chapter XIII.

The two surfaces of a thin lens are, therefore, tangent to each other at the pole, at the juncture of the principal axis with either surface.

60. Paraxial Imagery in a Thin Lens

From equation (9):

$$\frac{n'_1}{m'_1} - \frac{n_1}{m_1} = \frac{n'_1 - n_1}{r_1}; \quad \frac{n'_2}{m'_2} - \frac{n_2}{m_2} = \frac{n'_2}{\;}$$

where the subscripts 1, 2 represent the quantities for the two surfaces involved. We shall consider only the case where the thin lens is completely surrounded by a given medium, whose index of refraction is n. We then have $n_1 = n$; $n'_1 = n'$ (the index of refraction of the medium of which the lens itself is comprised); $n_2 = n'$; $n'_2 = n$. Also, because the lens has no thickness, $m_1 = m$; $m'_1 = m_2$; $m'_2 = m'$. Eliminating m_2:

$$\frac{1}{m'} - \frac{1}{m} = \frac{n' - n}{n}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \qquad (14)$$

The quantity on the right-hand side involves only constants of the lens itself, and, therefore, will be constant for a given lens. If we put m equal to infinity, we see that the quantity on the right really represents the reciprocal of the focal length of the lens according to the definition of focal length given in (49) and:

$$\begin{matrix} 1 & 1 & 1 \\ m' & m & \overline{f'} \end{matrix} \qquad (15)$$

Except for the sign between the two terms on the left-hand

side of this equation, it is identical with equation (7), and if m and m′ are transposed, the only effect is the change of the sign of f′. Consequently, there is only one numerical value for the focal length of a thin lens, its focal lengths being equal in value and opposite in sign.

The curvature of a surface is defined as the reciprocal of its radius (57) and given the symbol c, with suitable subscripts, 1 and 2, and c without subscript denotes the total curvature of a lens (the *algebraic difference* of the curvatures of the two surfaces). If we then replace the absolute indices n and n′ with the relative index of the two media, N, we can write:

$$\cdot = (N - 1)\,(c_1 - c_2) = (N - 1)c \qquad (16)$$

61. Image Equations Referred to the Principal Foci

We shall find use for the image equations referred to the principal foci instead of to the pole of the lens or surface. In

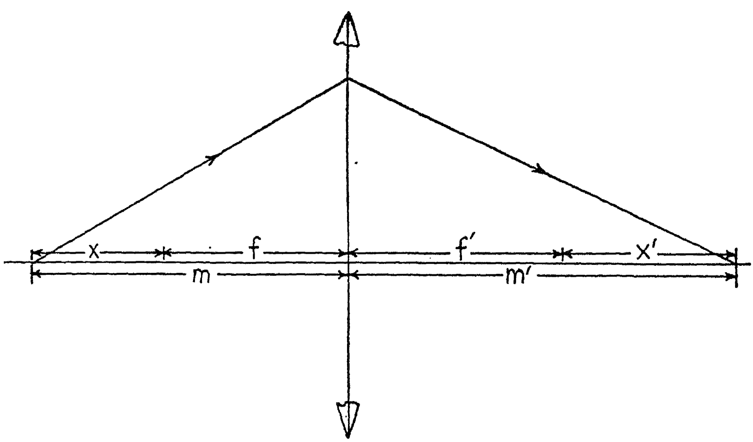

FIG. 32

Image equations referred to the focal points

appendix I, it is shown that the relations of the positions of object and image conform to the equation:

$$ff' = \mp xx' \tag{15a}$$

where x is the distance of the object from the primary focal point, F; x′ the distance of the image from the secondary focal point, F′, and x and x′ have the same sign conventions regarding direction of measurement as have m and m′ (fig. 32).

62. Focal Length of a Thin Lens

If we retain the definitions given in (41) that all distances falling to the left be negative and all distances falling to the right be positive, and also that the light be considered as incident from the left, we see, from equation (16), that f′ is positive for all converging lenses and negative for all diverging lenses, that is, that F′, the secondary focal point (because it comes second in going from left to right), lies to the right for a converging lens and to the left for a diverging lens. This means that, with parallel light, a converging lens will form a real image, and a diverging lens will form a virtual image.

63. Movement of Object and Image in a Thin Lens

Analysis of equation (15) shows that it gives the same graph as the equation for spherical refracting surfaces, in (52), fig. 28, except that the centers of the hyperbolas are now on a single line 45° from the axis (because, for the thin lens, f′ is numerically equal to f). This indicates that the movement of the image is in the same direction as that of the object, that object and image are coincident at the pole, that m′ approaches infinity as m approaches f, and that m approaches infinity as m′ approaches f′.

64. Optical Center of a Thin Lens

In appendix I it is shown that the position of the optical center of a lens is given by

$$AO = \frac{r_2 d}{r_1 - r_2} \tag{17}$$

where AO is the distance from the pole of the first surface to the optical center, and d is the thickness of the lens. r_1 and r_2 are the radii of the first and second surfaces, respectively, to be taken with the usual conventions as to sign. Evidently, when $d = 0$, as for a thin lens, AO is zero also, which means that for a thin lens, the optical center is at the common pole of the two surfaces.

65. Extra-Axial Object-Points

By the same argument as in (53), the image of a plane object perpendicular to the axis of a thin lens is also a plane perpendicular to the axis. Further, it is evident that the ray which passes through the optical center of a thin lens is completely unaffected by the transfer, for since the optical center is coincident with the pole, and the ray must leave the lens parellel to its path of incidence (58), the incident and refracted rays constitute a continuous straight line.

66. Graphical Construction of the Image Formed by a Thin Lens

In order to construct graphically the image formed by a thin lens, we make use of two known facts from the above, and, tacitly, of the knowledge that, for paraxial rays, extra-axial object-points form point images.

The thin lens is represented by a straight line perpendicular to the principal axis (fig. 33), and the principal focal points are marked by F and F′, at equal distances to the right and left. If desired, the true diameter of the lens and its form may be indicated as shown in the figure, using ↑ for a converging lens and Y for a diverging lens.

The object is indicated by the arrow **ab**. The construction consists of drawing the paths of selected rays. Knowing that

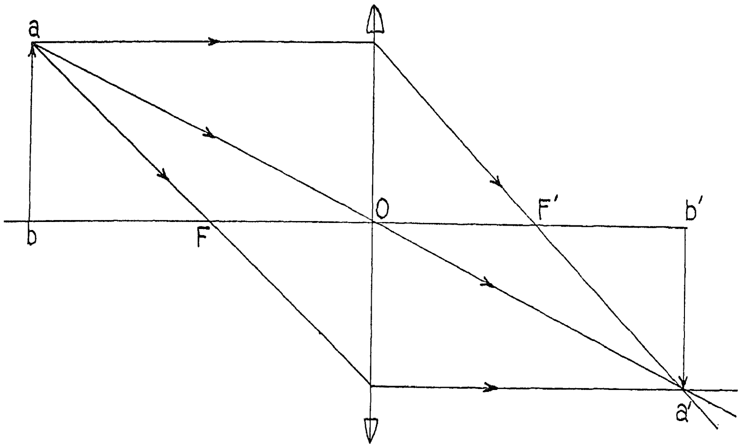

FIG. 33

Imagery in a thin lens

all object-points will have corresponding image-points, and that the image of an object perpendicular to the axis will also be perpendicular to the axis, we need only locate the image-point corresponding to the object-point **a**, and then draw a perpendicular from this image-point to the optical axis to obtain the entire image of the line **ab**. Since the point **a** sends out an infinite number of rays through the lens to the image-point **a**′, in order to locate this image-point it is necessary to draw only two rays, which may be selected at will. It would be possible to compute trigonometrically the path of any given ray from **a** through the lens, and find the intersection of two of them. But, from the previous discussion, we can determine the paths of certain rays from **a** by argument without the necessity of calculations.

We know from (49) and equation (15) that any ray parallel to the axis at the left of the lens must, upon refraction, pass through the secondary focal point F′. By the same reasoning, we also know that any ray passing through the primary focal

point F must emerge from the lens parallel to the axis. Furthermore, we know from (65) that any ray through the optical center will constitute a continuous straight line. These three rays are shown in fig. 33, and it is clear that we can locate the image-point a′ by drawing any two of them with ruler and compass.

67. Linear Magnification of a Thin Lens

The expression for the linear magnification of a thin lens takes a somewhat simpler form than for a spherical refracting surface, as given in (54), equation (13). By reason of the

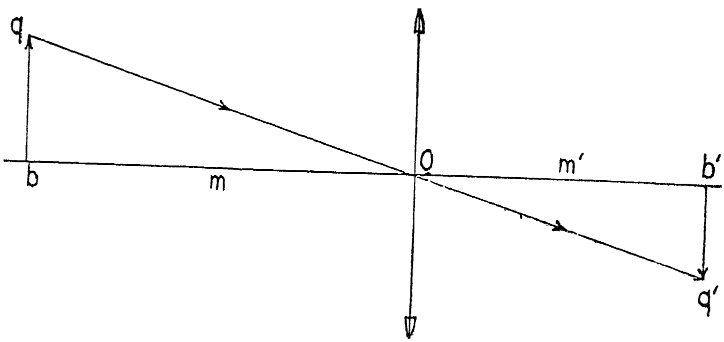

FIG. 34

Linear magnification of a thin lens

continuity of the chief ray through the optical center, we have from fig. 34:

$$M = \frac{b'q'}{bq} = \frac{m'}{m} \qquad (18)$$

The image is erect or inverted according as M is positive or negative.

68. Theorem of Lagrange

The theorem of Lagrange, discussed in (55), holds also for a thin lens. But in the case of a thin lens immersed in a

given medium, the index of refraction of the medium to the left of the lens will be the same as that of the medium to the right; in other words, object and image lie in the same medium. Consequently, n and n′ disappear from equation (13a) and:

$$y'u' = yu \tag{18a}$$

69. Refracting Power

It will have been noticed that in most of the equations for lenses, we have been dealing with the reciprocals of the quantities involved, since the equations are then in their simplest form. Since the focal length f′, a most important quantity, usually appears in the form $\frac{1}{f'}$, it would be convenient to give a name to this reciprocal and use a separate symbol for it. Therefore, the reciprocal of the focal length of a lens, or of a refracting or reflecting surface is known as the *refracting power* of the lens or surface. Its symbol is F.

The unit of refracting power is the diopter, or dioptry (abbrev: dptr.), and this is defined so that if the focal length f′ is expressed in meters, the reciprocal F′ represents the refracting power of the lens or surface in diopters. Thus, a lens of focal length 1 meter has a refracting power of 1 diopter; a lens of focal length 3 meters has a refracting power of ⅓ diopter; a lens of focal length ½ meter has a refracting power of 2 diopters, and so forth.

70. Non-Spherical Lenses

In (56) we restricted our definition of lenses to those with spherical curvatures. With extremely rare and special exceptions, all lenses in optical instruments are spherical lenses. However, lenses with other than spherical surfaces do exist, and are, in fact, widely and effectively used in spectacles. These spectacle lenses are called astigmatic, because the lack of symmetry of the surface produces the aberration known as astig-

matism. Because the human eye (chapter XII) is frequently afflicted with this aberration, the introduction of a lens with an equal and opposite amount of astigmatism is found necessary to correct the defect.

Astigmatic lenses may be of two types: cylindrical, in which the surface is a portion of a cylinder, that is, curved in one plane to a given radius, but not curved at all in the perpendicular plane; or toric, in which the curvatures in the two perpendicular planes are different. In the ophthalmic trade, the toric lens is usually called a cylinder, and a true cylinder is known under the term "flat-cylinder," the term toric being, for some peculiar reason, reserved for an ordinary spherical lens having a certain value of the "base-curve."

Occasionally in instruments we come across an astigmatizer, which is a cylindrical lens inserted for the purpose of producing a thin line for the image of a point. Such lenses are occasionally found in range finders and sextants, but their function is not associated with the functions of the other optical elements of the system. Astigmatism as an aberration is discussed in chapters XII and XIII.

Non-spherical, but still symmetrical surfaces, known under the general term *aspheric,* are quite frequently found in the applications of the reflecting surface to optical instruments. This is particularly true in astronomical reflecting telescopes, where paraboloidal, hyperboloidal, ellipsoidal, and other surfaces of revolution are frequently found. These will be discussed in chapter XVII.

CHAPTER IX

Thick Lenses—Combinations of Thin Lenses—Optical Systems

71. Definition of a Thick Lens

In the previous chapter we discussed the simplified case where the thickness of a lens was ignored in order to obtain simple relations between the distances of object and image, focal length, and so forth. This ideal situation never occurs in practice except with rough approximation. In case of lenses with finite thickness, the difference between the exact equations and those developed in chapter VIII is usually so small that the thin-lens equations are quite sufficient for the preliminary calculations of a system. However, for the final calculations, resort must be had to more exact expressions. For the original development of the relations to be discussed, we are principally indebted to Abbé and Gauss, who showed how certain simple concepts would permit the application of the thin-lens *form* of equation to the general problem of a thick lens.

A thick lens is composed of two spherical refracting surfaces with radii r_1 and r_2, respectively, separated by an interval d, measured along the principal axis (fig. 35). If the index of refraction of the medium to the left of the lens is n_1, that of the lens itself n_2, and that of the medium to the right of the lens n_3, then the focal lengths of the two surfaces of the lens are given by:

$$\frac{n_2}{f'_1} = \frac{n_2 - n_1}{r_1} = -\frac{n_1}{f_1}$$

and $\frac{n_3}{f'_2} \quad n_3 - n_2$

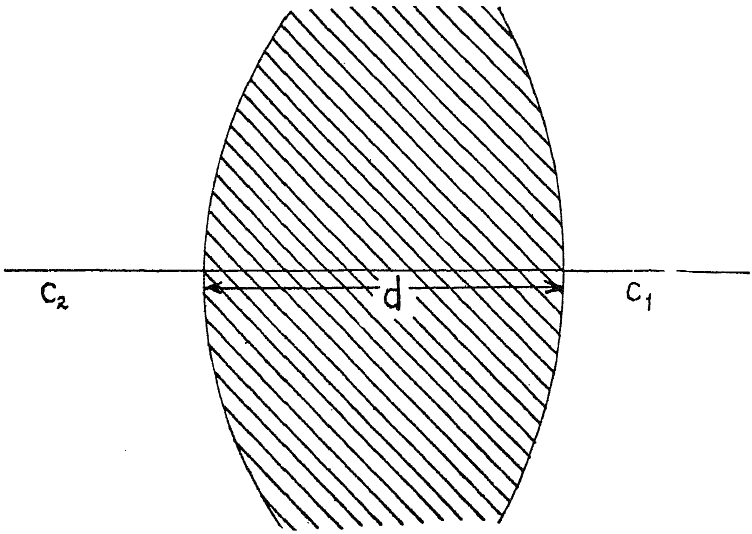

FIG. 35

The thick lens

We shall confine ourselves to the case of a thick lens of refractive index n, surrounded by air. Hence, $n_1 = n_3 = 1.00$; $n_2 = N$, so that

$$\frac{N}{f'_1} = \frac{N-1}{r_1} = -\frac{1}{f_1}$$

$$\frac{1}{f'_2} = \frac{1-N}{r_2} = -\frac{N}{f_2}$$

and the image equations become

$$\frac{N}{m'_1} - \frac{1}{m_1} = -\frac{1}{f_1}$$

and
$$\frac{1}{m'_2} - \frac{N}{m_2} = \frac{1}{f'_2}$$

where f_1 and f'_2 are the focal lengths of the first and second surfaces, respectively, *in air*.

If we combine the two equations above, recognizing that $m_2 = m'_1 - d$, and eliminate m'_1 between the two equations (appendix I), the imagery can be expressed in an equation of the form:

$$\frac{1}{m'_2 - \beta} \qquad \frac{1}{m_1 - \alpha} \qquad \frac{1}{F} \tag{19}$$

where:

$$\alpha = \frac{-f_1 d}{N(f'_2 - f_1) -}$$
$$\beta = \frac{-f'_2 d}{N(f'_2 - f_1) -} \tag{20}$$
$$F = \frac{-N f_1 f'_2}{N(f'_2 - f_1) - d}$$

so that, by adjusting the measurements of the object and image distances by the distances represented by α and β and adopting F as a focal length, we can express the imagery of a thick lens by the same form of equation as for the imagery of a thin lens. If we measure off the distances α from the *first* surface of the thick lens (taking care to use the proper signs for f_1 and f'_2, which will be opposite for a converging or diverging double-convex or double-concave lens), and the distance β from the *second* surface, we arrive at two points known as the *principal points* of the thick lens, and we note that a thin lens of focal length F would form an image at $m'_2 - \beta$ of an object located at $m_1 - \alpha$ (fig. 36).

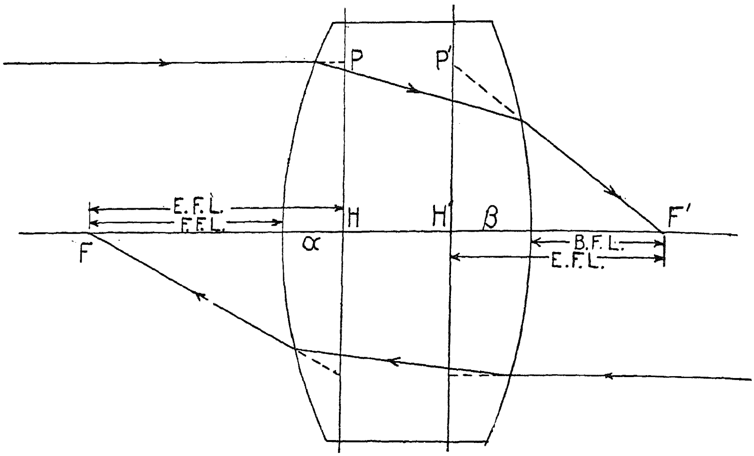

FIG. 36

Principal planes of a thick lens

72. Equivalent Focal Length

The quantity F is called the *equivalent focal length* of the thick lens, because it is the focal length of the *equivalent thin lens.* The equivalent focal length is indicated in fig. 36, in addition to the "front focal length" and "back focal length," terms frequently used in descriptions of optical elements, as these distances can be mechanically measured, whereas the position of the principal planes calls for a mathematical determination.

73. Principal Planes of a Thick Lens

The perpendicular planes erected through the principal points defined in (71) are known as the *principal planes* of the thick lens. We saw that for a spherical refracting surface (52) and for a thin lens (63) the object and image coincided at the pole. For a thick lens, object and image coincide in the principal planes, the image being in one principal plane when the object is in the other. The principal planes are named primary and

secondary, the primary principal plane being that one associated with the medium containing the incident light (plane through H in fig. 36).

In the principal planes, the magnification is unity, for in equation (18), $m' = m = 0$, and as m'/m approaches 0/0, M approaches unity. We will see that a knowledge of the location of the principal planes is essential to the development of the numerical relations in an optical system.

Since the principal planes indicate the location of the equivalent thin lens, any ray incident at a point P in the primary principal plane (fig. 36) will emerge from the secondary principal plane at a point P′, such that the height of P′ above the principal axis is equal to the height of P. And, since the principal points H, H′ represent the optical center of the equivalent thin lens, any ray incident at H must emerge at H′ parallel to its path of incidence, that is, at the same convergence angle, such that $u' = u$.

74. Nodal Planes and Focal Planes

When the medium on one side of the thick lens is different than the medium on the other side, the second condition of the previous section, namely, that the convergence angles are the same for the incident and emergent ray through H, H′ does not hold. But in this case, there are two other points on the axis where this condition does prevail, and these points are known as the *nodal points,* and the planes perpendicular to them are the *nodal planes.* The nodal points are separated by the same interval as are the principal points, and are, therefore, symmetrical.

The planes perpendicular to the principal focal points, F and F′, are known as the primary and secondary *focal planes,* respectively. The principal points, the focal points and the nodal points are frequently referred to as the cardinal points of an optical system. When the thick lens is surrounded by a given medium, the nodal points are coincident with the principal points. In this book we shall not discuss the condition where a

lens separates two different media, since it will not arise in any of the instruments which we discuss in any detail except the oil-immersion microscope, which is not discussed mathematically.

The principal planes are especially important because they are characteristic of any optical system, no matter how many lenses or surfaces it contains. Actually, the thick lens is an *optical system,* composed of two spherical refracting surfaces, and a compound lens consisting of many surfaces may be treated as a single thick lens.

75. Imagery in a Thick Lens

We saw in (71) that the imagery in a thick lens can be represented by equation (19).

Since a thick lens is equivalent to a thin lens located at the principal planes, the formula for linear magnification becomes:

$$M = \frac{y'}{y} = \frac{m' - \alpha}{m - \beta} \tag{21}$$

The theorem of Lagrange, for a thick lens, remains:

$$y'u' = yu \tag{18a}$$

the indices canceling out because the index of the object medium is equal to that of the image medium. If the medium on one side of the thick lens were not the same as that on the other side, the equation would take the form:

$$n'y'u' = nyu \tag{13a}$$

76. Two Thin Lenses in Combination

In the special case where the optical system consists of two *thin* lenses, separated by the interval d (fig. 37), we obtain:

$$f' = \frac{f'_1 f'_2}{f'_1 + f'_2 - d} \tag{22}$$

and, for the location of the principal planes of the system:

$$\alpha = \frac{f'_1 d}{f'_1 + f'_2 - d}$$

$$\frac{f'_2 d}{f'_1 + f'_2 - d}$$

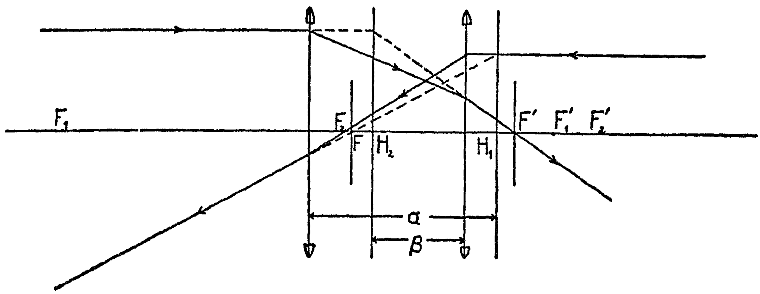

FIG. 37

Combination of two thin lenses

The location of the primary and secondary principal planes of a combination of two thin lenses corresponds to the required positions of a single thin lens equivalent to the combination, the primary principal plane corresponding to the position for the equivalent lens if the light is incident from the left, and the secondary principal plane its position for light incident from the right. In order to achieve the same linear magnification as the combination, the equivalent thin lens must have the focal length given by equation (22).

In the case of a combination of two positive thin lenses, the principal planes are "crossed," that is, the primary principal plane lies to the right of the secondary principal plane.

77. Multiple Thin Lenses in Contact

In the case of several thin lenses in contact, the equation for the focal length of the combination reduces to:

$$\frac{1}{f'} = \frac{1}{f'_1} + \frac{1}{f'_2} + \frac{1}{f'_3} + \cdots + \frac{1}{f'_k} \qquad (22a)$$

and, since this case is considered as a thin lens, the principal planes are coincident at the pole.

78. Combination of Two Optical Systems

Almost every optical instrument can be considered to be formed of the combination of two optical systems, and since any optical system (71) may be treated by the equations for a thin lens provided we take our measurements from the principal planes of the system, it is possible to discuss the combination of two optical systems as a combination of two thin lenses.

We have already (76) developed expressions for the focal length and position of the principal planes of a combination of two thin lenses, and we can discuss the effect of a variation of the distance of separation d, where d in this case is the distance from the secondary principal plane of the first system to the primary principal plane of the second system, that is, the distance separating the two *equivalent thin lenses.*

There are three possible cases: where both components are of positive focal length, where both components are of negative focal length, and where one component is positive and the other negative.

A. Both Components Positive

The focal length of the combination, f', will be a minimum when $d = 0$, that is, when the two lenses are in contact, in which case the equation reduces to $\frac{1}{f'} = \frac{1}{f'_1} + \frac{1}{f'_2}$, as we found in (77). As the separation grows, the focal length grows also, until when $d = f'_1 + f'_2$, the focal length is infinite. The focal length then becomes negative for separations greater than $f'_1 + f'_2$.

When d is less than $f'_1 + f'_2$, the combination represents an objective, a magnifying glass, or an ordinary eyepiece. When d is equal to $f'_1 + f'_2$, both focal planes lie at infinity, and we have the "afocal" or *telescopic* system. The simplest form of a telescope is the Keplerian, consisting of two positive lenses, the secondary focal plane of the first lens coinciding with the primary focal plane of the second lens, thus satisfying the condition, $d = f'_1 + f'_2$.

When d is greater than $f'_1 + f'_2$, the focal length is negative, and we have the optical system of the compound microscope.

B. Both Components Negative

In this case, the focal length of the combination is always negative, and increases numerically as d increases. There are no important applications of this type of system.

C. One Component Positive, the Other Negative

1. When the negative lens has the longer focal length, the combination in this case is always positive, and the focal length is a maximum when the lenses are in contact, diminishing as d increases. This type of combination is sometimes used in transit instruments (chapter XXIII), and occasionally for photographic objectives.

2. When the negative lens has the shorter focal length, and d is small, the combination has a negative focal length, which becomes infinity when $d = f'_1 + f'_2$. Again we have a telescopic system, this time the Galilean telescope, which produces an erect instead of an inverted image. As d becomes greater, the focal length remains positive and diminishes. This condition represents the optical system of the telephoto lens (181).

79. Linear Magnification of a Thick Lens

Equations (18) and (18a) are unaltered by application to a thick lens, if the distances m and m′ are measured from the principal planes, as was shown in (75). The equation for the

linear magnification referred to the focal points (61) becomes:

$$M = \frac{y'}{y} = -\frac{f}{x} = -\frac{x'}{f'} \tag{23}$$

where the sign of M indicates an erect or inverted image, according to its being positive or negative.

80. Longitudinal Magnification

We sometimes wish to consider the elongation of the image along the principal axis with respect to the elongation of the corresponding object. If we let the distance of one end of the object from the primary focal point be x, and its length along the axis be dx, then the corresponding quantities for the image will be x′ and dx′. From equation (15a) we have

$$x' = \frac{ff'}{\cdot}$$

Differentiating, we obtain

$$dx' = -\frac{ff'}{x^2}\,dx$$

Now, the ratio between the lengths of object and image is $\frac{dx'}{dx}$, which we shall call the *longitudinal magnification*, and give the symbol L. Thus:

$$L = \frac{dx'}{dx} = -\frac{ff'}{x^2} \tag{24}$$

81. Angular Magnification

When object or image, or both, are located at infinity, the equations for linear and longitudinal magnification become meaningless, as does the concept of magnification discussed in these equations. Since many optical systems fall into this category, we must develop a method of measuring magnification

for them. Such a method is represented by the *angular magnification* or convergence ratio.

Let M (fig. 38) be the point where a ray from an extra-axial object-point crosses the optical axis, and P the point where it crosses the primary focal plane. Also, M′ and P′ are the corresponding points for the image ray. Let θ and θ' be the convergence angles at M and M′ respectively. Now a ray parallel to the axis through P will emerge parallel to any other ray through P, because P is in the focal plane, thus it will be parallel to the particular ray M′P′. Similar conclusions apply to the parallelism of MP and the emerging ray leaving P′ parallel to the axis. But, rays parallel to the axis must pass, after refraction, through the focal points F and F′.

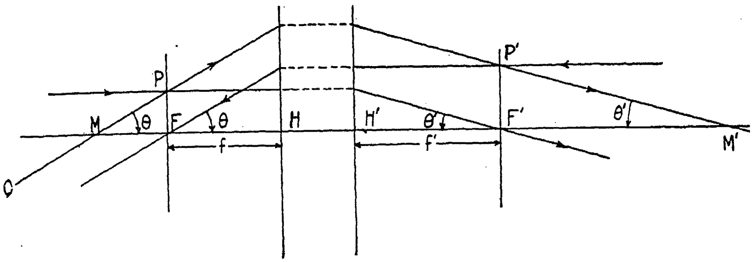

FIG. 38

Angular magnification

Therefore, from the diagram, we have:

$$\tan\theta = \frac{FP}{MF} = \frac{FP}{x}$$

$$\text{and } \tan\theta' = \frac{F'P'}{F'M'} = \frac{F'P'}{x'}$$

But:

$$f' = \frac{F'P'}{\tan\theta}$$

$$\text{and } f' = \frac{FP}{\tan \theta'}$$

and, finally:

$$\text{Angular Magnification} = MA = \frac{\tan \theta'}{\tan \theta} = \frac{f}{x'} = \frac{x}{f'} \qquad (25)$$

Here, also, the sign of MA indicates an erect or an inverted image, according to its being positive or negative.

CHAPTER X

Total Reflecting Prisms

82. Introduction

The subject of prisms has already been discussed in some detail in chapter VI. It was there shown what circumstances determine that total reflection shall take place at the second face of a prism.

This principle of total reflection within a prism is of great value in the design of optical instruments, and is especially made use of in military instruments. In most cases, the prisms used are not the simple affairs discussed in chapter VI, where only two faces were considered. It is evident that a prism may have many faces, so that, if total reflection takes place at the second face, the light may be received at a third, and if total reflection takes place here, the light may be received at a fourth surface, and so on, the number of possible faces being infinite. The principle of cutting a diamond is that of making of it a total reflecting prism with a large number of faces. Due to the very high index of refraction of a diamond, its critical angle is small, and light entering a particular face will be subject to a great number of internal reflections, finally emerging from some face considerably removed from the incident face, thus giving rise to the characteristic sparkle.

83. Imagery and Inversion in Total Reflecting Prisms

The imagery in a total reflecting prism is, obviously, exactly the same as the imagery in a plane mirror or in a series of plane mirrors (17,18). It was also explained (10) that the image produced by a single plane mirror is *inverted* in one plane.

The *axis of inversion* (the axis, lying in the plane of the image, about which the image is apparently rotated 180° to produce an inversion) is perpendicular to the *plane of incidence* (15). Therefore, each reflecting face of a total reflecting prism introduces an inversion about the specified axis, and the total effect of the prism may be determined by adding up these inversions about the various axes.

84. Equivalence of Inversion and Rotation

If we select two axes, lying in the plane of the image, at random (fig. 39) and let the angle between them be θ, then the following rule will hold:

Inversion about the axis AA′ is equivalent to inversion about the axis BB′, plus rotation about the central ray through 2θ. This is shown by example in fig. 39.

By the same procedure, we can show that inversion in two mutually perpendicular planes is equivalent to a rotation through 180° about the central ray as axis.

Also, if the effect of a prism is to deviate the line of sight through 180°, this deviation is exactly the same as an inversion about the axis of deviation. This phenomenon effectively permits the observer to get behind the object and view it from that vantage point. The effect can be easily seen by holding a transparent picture between oneself and a plane mirror. The direct view of the picture and its image in the mirror are identical, the result of the summation of the inversion produced by the mirror and the 180° deviation of the line of sight. This is not the same thing as using a mirror to view something behind oneself, in which case the image is *inverted* as compared with the observer's normal view, which would require that he turn around.

We can state the following general rules for inversion in total reflecting prisms:

1. If the prism has an odd number of reflecting faces, there is inversion in one plane.

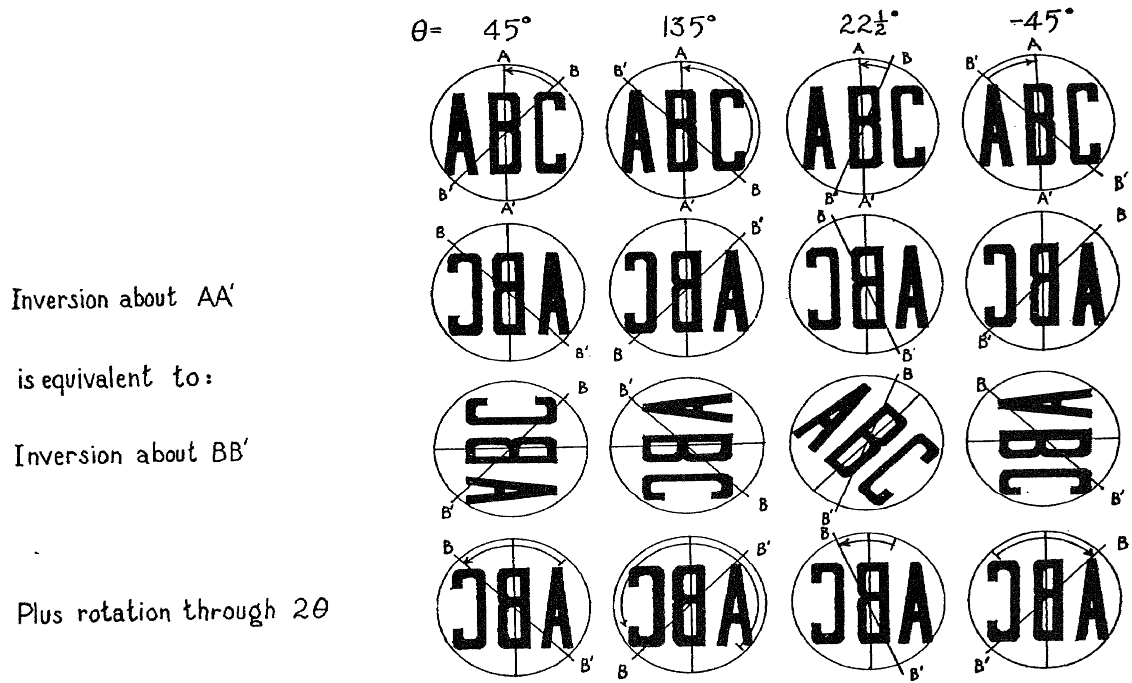

FIG. 39

Equivalence of inversion and rotation

2. If the prism has an even number of reflecting faces:
   a. If the planes of incidence of the surfaces are so related that there is an odd number of inversions in each of two mutually perpendicular planes, the prism gives inversion in two planes.
   b. If the planes of incidence of the surfaces are so related that there is an even number of inversions in each of two mutually perpendicular planes, or if the planes of incidence of the surfaces are all parallel, the prism gives no inversion.
3. If the inversion planes of the prism are not mutually perpendicular, the prism will introduce a rotation of the image.

If the prism deviates the line of sight through 180°, this will constitute an additional inversion about the axis of deviation.

85. Purposes of Prisms

Total reflecting prisms are used in optical instruments to accomplish one or more of three results:

1. To change the direction of the line of sight, usually through 90°, but occasionally through other angles.
2. To introduce an inversion in either one or two planes, to counteract the inversion of other prisms or lenses. This category includes *erecting systems* and prisms used for rotating the field of view.
3. To displace the optical axis parallel to itself, as in periscopic and stereoscopic instruments.

86. Relative Advantages of Prisms and Mirrors

It is often argued that a series of one or more plane mirrors would achieve the same effect as a total reflecting prism, and that the saving in light transmission due to absorption in the prism would be an additional advantage, it being understood that mirrors are less expensive than prisms.

In instruments where the loss of light through absorption in a prism would be an important factor, there is much merit in the argument. But in instruments used for terrestrial observation, the problem of light absorption is hardly ever worthy of consideration, and in these instruments prisms possess certain inherent advantages which will justify their continued use.

In the case of a prism with more than one reflecting surface, the relation of the reflecting surfaces to one another is fixed and permanent. A series of mirrors would have to be carefully mounted to permit precise adjustment, and any rough handling would undoubtedly disturb the relations and put the instrument out of adjustment until repaired. Further, any mirror used in an optical instrument must be coated on the front surface because a back-surfaced mirror will produce multiple images due to reflection from both front and back surfaces. But these front-surfaced mirrors cannot be protected from damage by a thick coat of paint, as is possible with back-surfaced mirrors, and they require frequent recoating. Until recent years, silver was the only mirror surface available, and this tarnishes readily. Today, aluminum and aluminum alloys, deposited by vaporization, have almost entirely replaced silver for front-surfaced mirrors, and have been a most welcome improvement, since they will not tarnish. However, both silver and aluminum coatings are much softer than the glass of a prism, and much more easily damaged. An important additional advantage of prisms lies in the fact that the reflection is from the *inside* surface and thus is not affected materially by dirt and dust on the outside. However, conditions which generate dust and dirt on the reflecting surfaces of prisms will also generate them on the entrance and exit faces.

It is for these reasons that prisms are frequently found in instruments, although the expense of installing them may be considerably more than for mirrors. This is especially true in military instruments, which must be so constructed as to

withstand rough handling without damage or maladjustment. There is, however, a considerable trend toward the use of aluminized mirrors in instruments where the factors favoring prisms are not of outstanding importance. In instruments where very large prisms would be required, mirrors are generally used, since the expense of huge blocks of optical glass suitable for large prisms would be prohibitive. Moreover, the absorption of light in a large prism would be very great, and might reach significant values even for observation instruments.

87. Principles of Prism Design

It is not possible to arrive at a generalized mathematical formula for the design of a prism to produce certain specified effects. Designing a prism is a process of working surface by surface according to the law of reflection. It is not necessary to meet all the conditions for total reflectivity enumerated in (37). At any surface where the angle of incidence is less than the critical angle, a silver coat may be introduced, and since the reflection is from the inside surface, this will be a back-surfaced mirror and can be protected by paint. Such surfaces should be avoided, however, unless other decided advantages result, since a silvered reflecting surface is never quite as satisfactory as a surface where total reflection occurs because of the angle of incidence, as the reflection in the former case is never quite 100%.

A few general and perhaps rather obvious principles should, however, be borne in mind in the design of total reflecting prisms. The length of the path of light through the prism should be kept as short as possible, to reduce absorption to a minimum; therefore, the number of reflections should be kept at the minimum which will achieve the purpose desired. It is undesirable to have three reflecting surfaces, all producing inversion about the same axis, when one surface would suffice. In fig. 40, prism b produces the same effect as prism a, and is infinitely preferable.

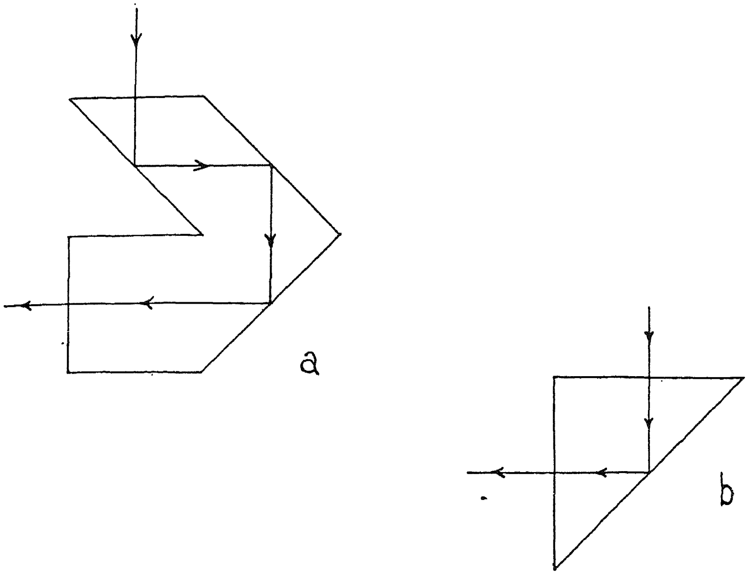

FIG. 40

Right (b) and wrong (a) designs for a 90° deviation prism

Entrance and exit faces should be perpendicular to the incident light wherever possible, to avoid undesirable effects due to dispersion (104). The optical effect of a prism upon a system is exactly the same as the effect of a plane-parallel plate, so far as considerations of field of view, focal length, aberrations, etc., are concerned, the thickness of the equivalent plate being equal to the path of the chief ray in the prism. In the designing of optical systems, total reflecting prisms are usually treated as plane-parallel plates.

88. Types of Total Reflecting Prisms

A. Prisms for changing the direction of the line of sight

The most common type of prism used for this purpose is the right-angle, or 45–90 prism, shown in fig. 41. This prism

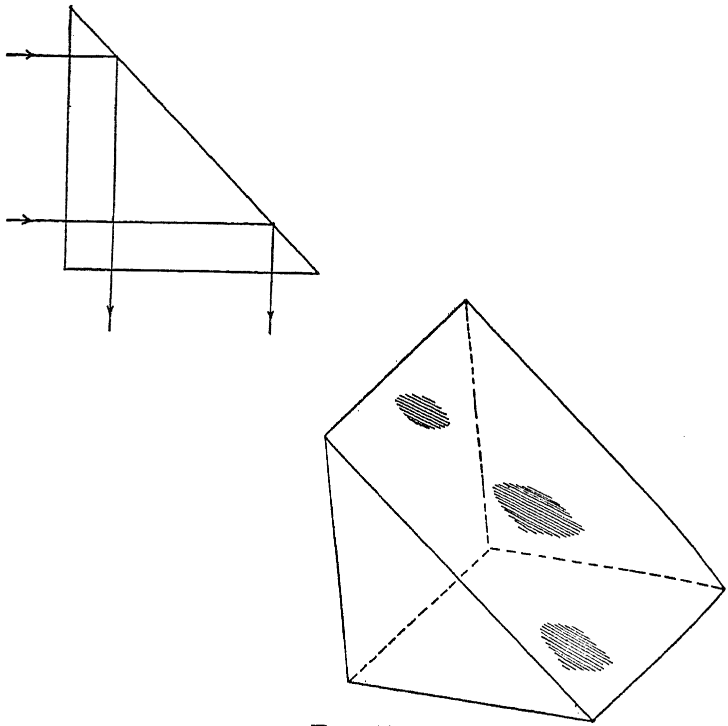

FIG. 41

Right-angle prism

has but a single reflecting surface, and consequently will introduce inversion in one plane. It is most frequently used in pairs, the inversion of one counteracting that of the other.

Another common type of 90° deviation prism is the penta prism (fig. 42). This prism has two reflecting surfaces, for which the planes of incidence are parallel, thus it introduces no inversion. The great advantage of this prism is the fact that its deviation is always exactly 90° (subject to the error of the prism itself, which will not exceed 5′ of arc) for incident rays at any angle through the entrance face. By adjusting the angle between the reflecting faces, the penta prism may be

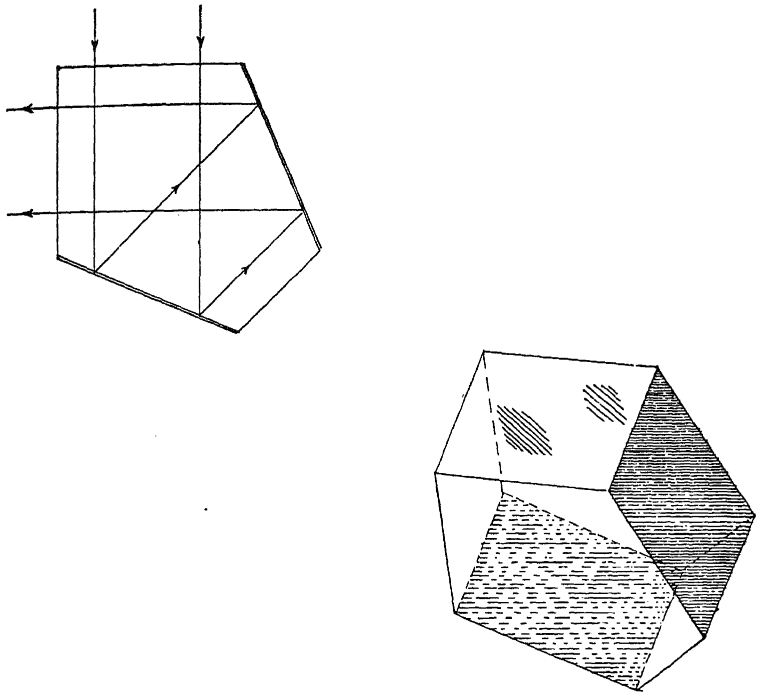

FIG. 42

Penta prism

The two reflecting faces must be silvered.

made to give constant deviation through a wide range of selected angles. It is not, however, commonly found except in the 90° deviation form shown in fig. 42.

Prisms of the general type shown in fig. 43 can be made to give deviation of almost any desired angle θ. Since there are two reflecting surfaces, each producing inversion about the same axis, the prism has no effect on the orientation of the image.

Another general type of two-reflection prism is shown in fig. 44. This can also be made to produce deviation through

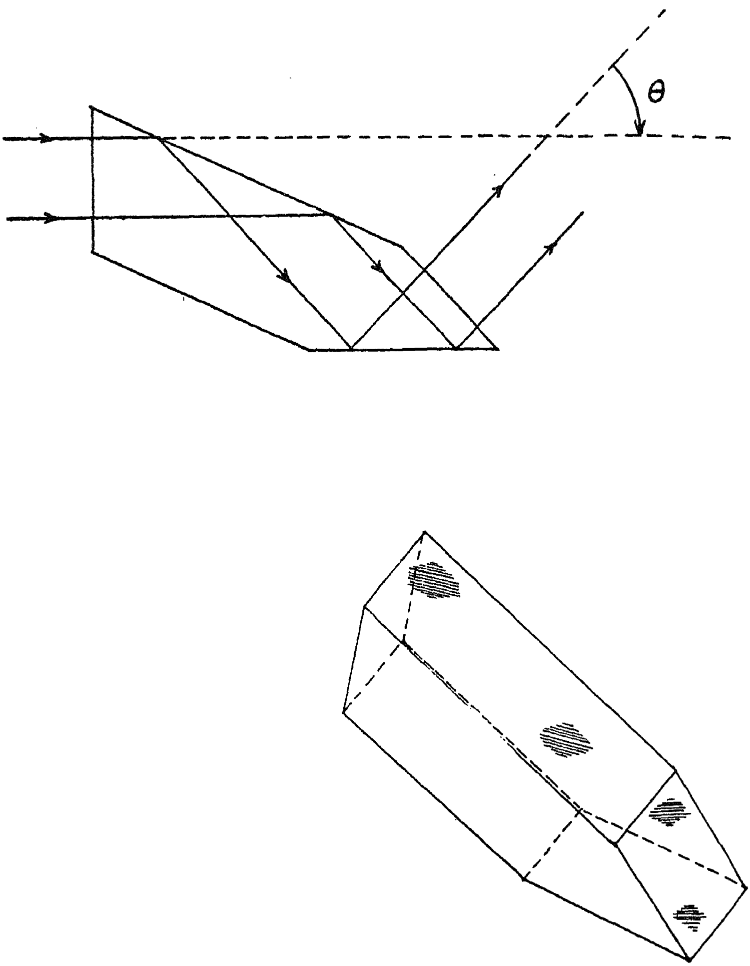

Fig. 43

Deviation prism

a large range of possible angles ϕ. This type is less desirable than the type shown in fig. 43, since the light path is usually slightly longer.

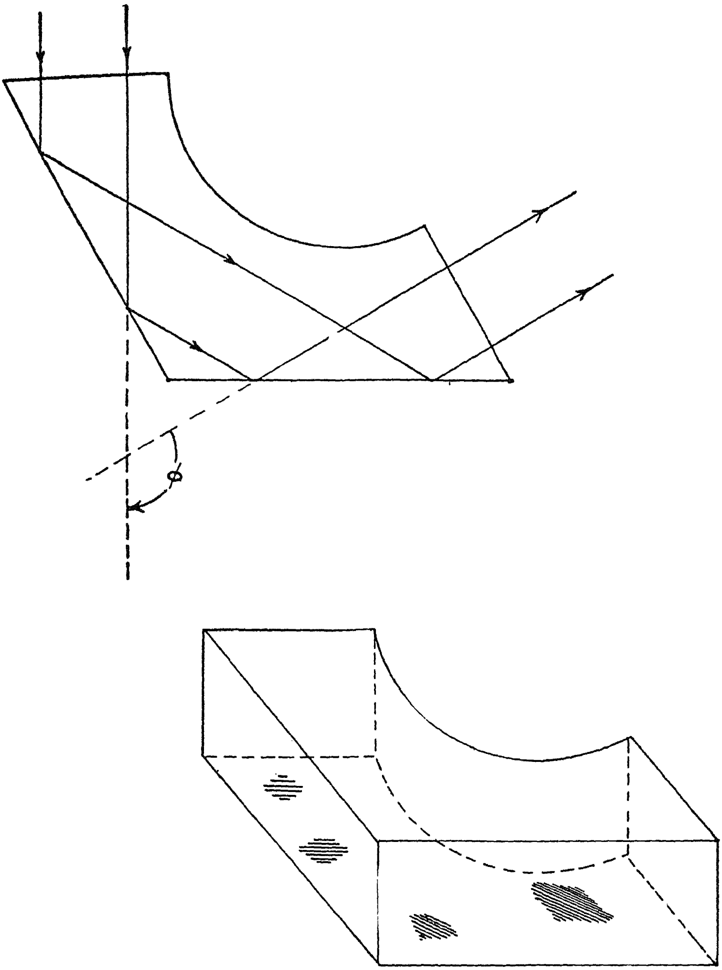

FIG. 44

Deviation prism

B. Prisms for producing an inversion

Conditions requiring inversion in a single plane arise principally because of an inversion produced elsewhere in the in-

strument by a prism used for some other purpose. In such cases, it is usually advisable to redesign the other prism by adding the new prism to it, that is, by putting both prisms at the same point in the instrument. Occasionally, however, a movable prism in an instrument such as a panoramic periscope will rotate the image, and it will be necessary to introduce a single-inverting prism to bring the image back into its proper position. By the principles outlined in (84), this compensating prism should be rotated about the optical axis through half the angle it is required to rotate the image. Also, this prism must be of a type which does not deviate or displace the optical axis. Two forms are shown in fig. 45, the Dove prism, with one reflection, and another type (unnamed) which has

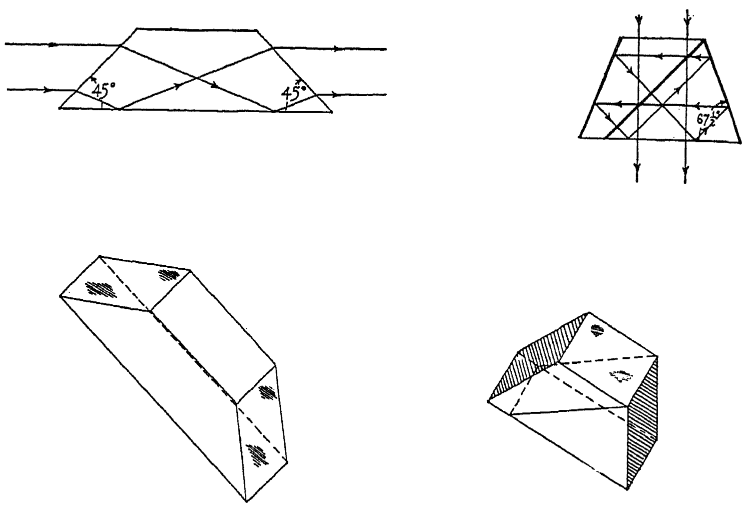

FIG. 45

Two forms of rotating prism

the advantage of taking up less space and producing no aberration (perpendicular incidence and emergence of rays), but the disadvantage of having five reflecting surfaces, two of which must be silvered.

Another type of single-inverting prism is the so-called *triple-mirror,* with three reflecting faces. This is really a corner of a cube, produced by a plane perpendicular to the hypotenuse. Its advantage is that it produces a deviation of 180° for any incident ray whatever, thus making its location unimportant (18)* (fig. 46).

There are many types of prism for producing inversion in

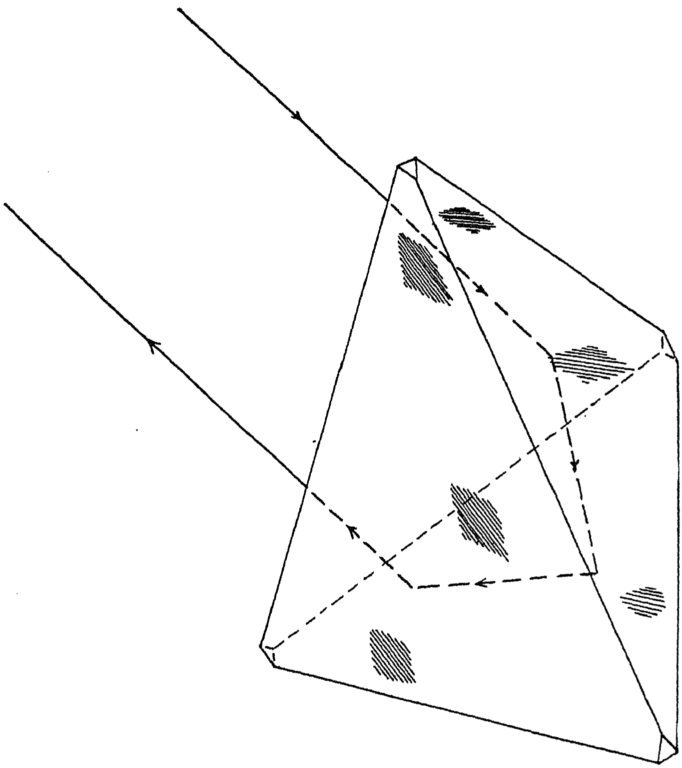

FIG. 46

The "triple mirror"

* The principle of the triple mirror is applied in the reflector type of road sign. Small reflectors, shaped as the corner of a cube, return the light from the motorist's headlamps.

two planes, for such a prism constitutes an *erecting system,* to be discussed in chapter XIV.

C. Prisms for producing a displacement of the optical axis

It is sometimes necessary to displace the optical axis of an instrument parallel to itself, and to do this without inverting the image calls for a prism with two (or four, or six, etc.) reflecting faces. The usual prism for this purpose is the rhomboidal prism (fig. 47). This function is sometimes combined with that of an erecting system, as in the Leman prism, which will be discussed in chapter XIV (fig. 75).

Practically all these displacement prisms are *constant-devia-*

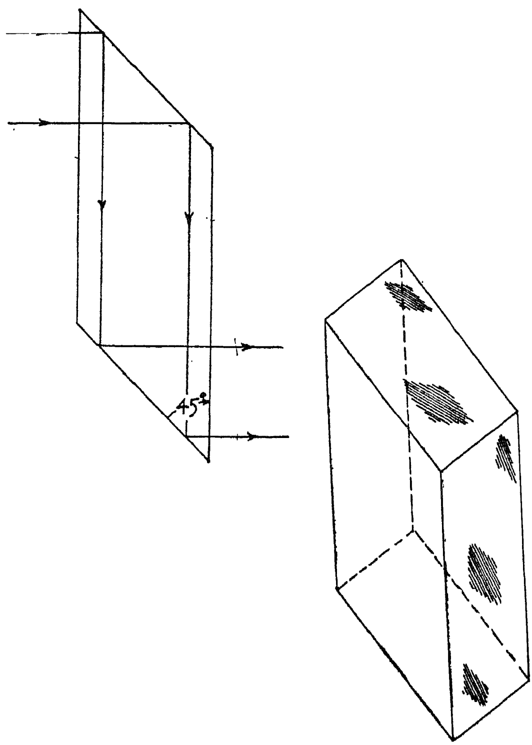

FIG. 47

Rhomboidal prism

tion prisms, the deviation of the rays being independent of their original angle of incidence.

89. Roof Prisms

Many common erecting systems are of the so-called *roof* prism type, about which we should say a few words in this chapter. The principle of the roof prism is that of the two inclined mirrors in (18) where the angle of inclination is 90°. In this case the planes of incidence for the two reflecting surfaces are mutually perpendicular, and inversion in two planes results (fig. 48). There have been designed many types of

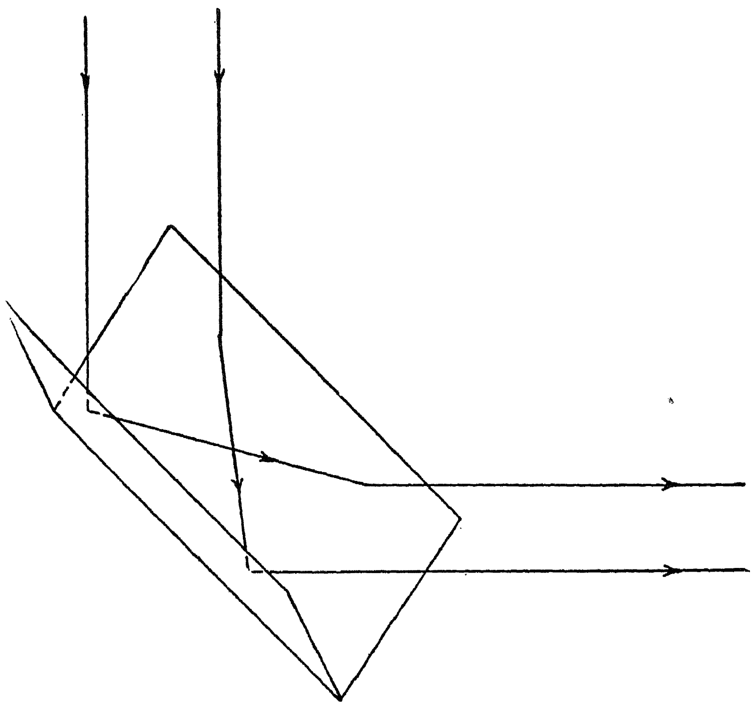

FIG. 48

Principle of the roof prism

roof prisms, most of which have too many reflecting faces to be really efficient.

It will be seen from the discussion in (18) that if the angle of inclination is not exactly 90°, the image produced by reflection from both faces will not be single, but multiple (double). Experience has dictated that the tolerance of this 90° roof angle is approximately 2″ of arc (the apparent size of a dime at 1¼ miles), which makes roof prisms exceedingly expensive and difficult to produce.

CHAPTER XI

Aperture and Field of an Optical System

90. Effect of a Diaphragm on an Optical System

Diaphragms find frequent use in optical systems, and their effect upon the system is a subject of much importance. A diaphragm may be defined in general terms as a limited opening controlling the size of the bundle of light rays which can pass through the plane where the diaphragm is located. To study the effect of such a limited opening, let us consider a thin lens (fig. 49). The effects which we are to study will be the same for a thin lens as for a complete optical system.

In fig. 49 (a) the thin lens is shown without a diaphragm, and a bundle of rays from the object-point P covers the entire surface of the lens. Similarly with a bundle from the object-point Q.

In (b) we have placed a diaphragm immediately before the lens, and the only effect of this diaphragm is to reduce the diameter of the admitted bundles.

If the diaphragm is placed at a distance from the lens, however, as in (c), a different effect is evident. The size of the diaphragm in this case is such that the admitted bundles of rays are of the same diameter as in case (b), but the bundle from Q passes through a different portion of the lens than the bundle from P. While in case (b) the result was effectively to reduce the diameter of the lens, in case (c) the effect is to make the entire diameter of the lens necessary in order to admit the bundle from Q.

In case (d) the diaphragm has been placed at some distance *behind* the lens, and the situation is just the reverse of that in case (c).

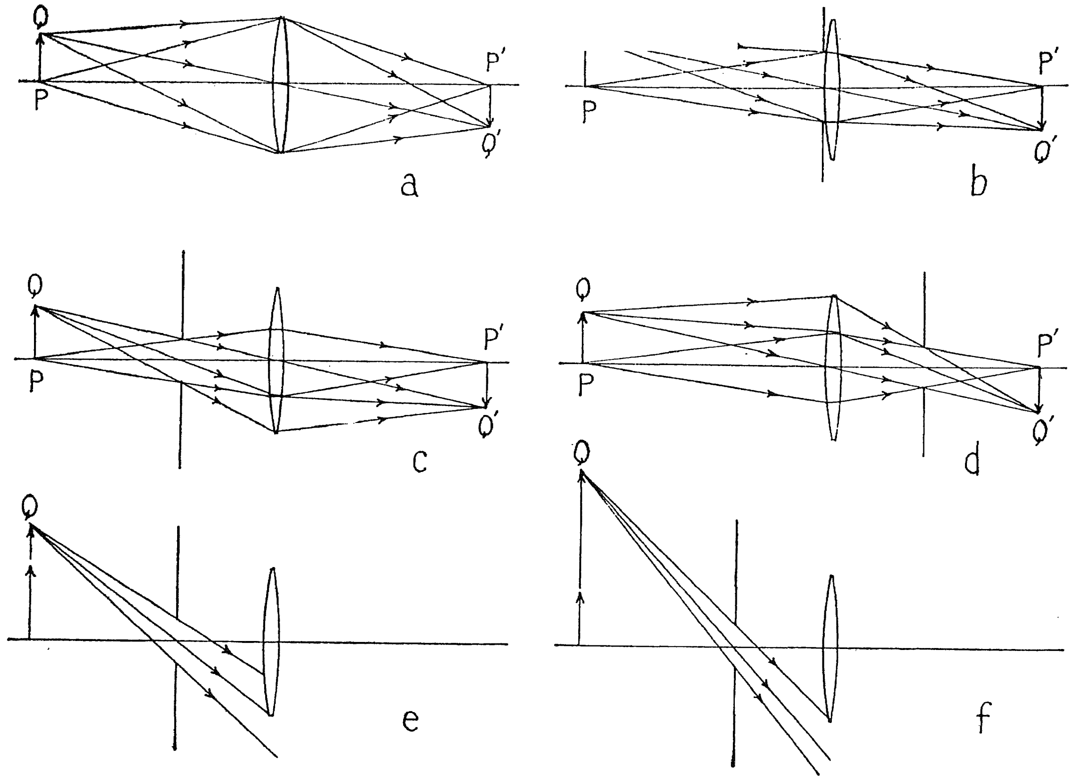

FIG. 49
Diaphragms on a thin lens

It immediately becomes apparent that the effect of a diaphragm placed at a distance from the lens is going to be to limit the *field of view,* that is, the cone in which object-points must be located in order for the lens to form images of them. In cases (a) and (b) any object-point lying on the left of the lens can give rise to a bundle of rays which will pass through the lens, and these bundles will all be of approximately the same size unless the object-point lies at a very considerable angle from the optical axis. When a diaphragm is interposed, however, we do not have to go very far from the axis with an object-point before the diaphragm begins to limit the size of the bundle which can enter the lens. In (e) we note that for the object-point Q, the bundle which can enter the lens has been reduced by one-half. In (f) the object-point Q is so situated that no light from it can enter the lens at all.

It is evident that Q in (f) represents the extreme limit of the field of view of the lens. And it is also evident that Q in (c) and (d) represents the limit of the *fully-illuminated* field of view, for any object-point farther from the axis than Q in (c) or (d), such as Q in (e), will have its effective bundle of rays limited by the diaphragm, and the light that finally arrives at the image-point will be deficient in quantity with respect to the light which arrives from object-points lying between Q and P in (c) and (d).

The effect of falling off in brightness of image points as we proceed away from the principal axis is often referred to as the *vignetting effect,* taking its name from the procedure often used in portrait photography to reduce the intensity of the background.

It is reasonable to suppose that this is, in general, an undesirable property in an optical instrument, and that it would be advisable to so adjust the diaphragms of the instrument as to eliminate it. How this may be done is illustrated in fig. 50.

A system composed of two thin lenses, I and II, is shown. The object-point Q is the limit of the fully illuminated field

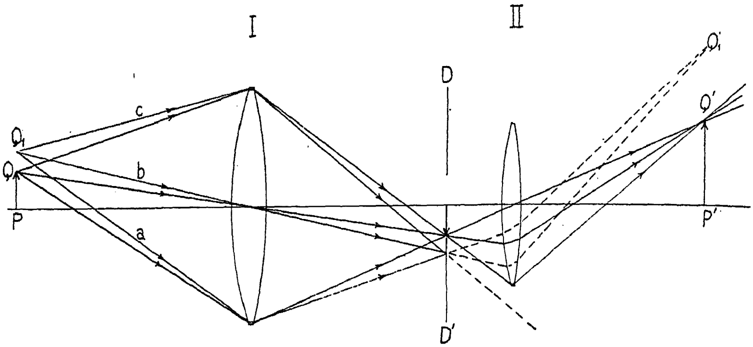

FIG. 50

Field stop in an optical system

of view for lens II, since the clear diameter of lens I acts as a diaphragm for lens II (a common occurrence in optical instruments). Without any further diaphragming, rays (a) and (b) from an object-point Q_1, farther from the axis than Q, would enter lens II, as indicated by the dotted lines, and give rise to a poorly illuminated image-point at Q'_1. If, however, a diaphragm is introduced at the image of PQ in lens I, (D,D'), then no rays from any object-point farther from the axis than Q can enter lens II, and the diameter of the image produced at P'Q' will be restricted to the diameter P'Q'.

In fact, it will be readily seen that an image of the diaphragm DD' will be produced by lens II, and that it will be located in the plane of the image P'Q', so the result will be an image of the field of view reproduced in the clear center of the image of the diaphragm.

91. Types of Diaphragms

There are three types of diaphragms used in optical systems. Those illustrated in fig. 49 are *aperture stops,* since their function is to restrict the diameter of the bundle of rays which can enter the instrument. In the event of the absence of a material

aperture stop, the cell of some lens in the system performs the function of restricting the diameter of the entrant bundle and becomes the aperture stop.

The diaphragm illustrated in fig. 50 is a *field stop,* since its function is to restrict, or *stop down,* the field of view to that region which is fully illuminated. This field stop is used almost without exception in optical instruments, to eliminate the undesirable vignetting effect. It must be located in a plane where a real image is formed, and for this reason is most frequently found, in a telescope, just in front of the eyepiece.

It is frequently found desirable to place *antiglare* diaphragms in an optical system (fig. 51) to prevent any light reflected from the inside of the tube of the instrument from finding its way into the final image. The size of these antiglare diaphragms should be such as to permit the passage of a truncated cone of rays whose base is the lens diameter and whose top is the field stop.

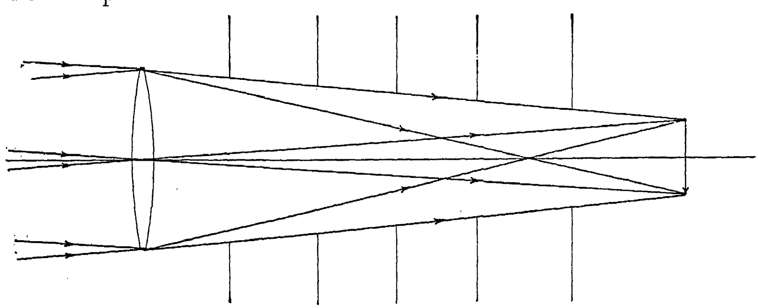

FIG. 51

Anti-glare diaphragms

It is customary in telescopic instruments for the aperture stop to be represented by the cell of the objective lens. In cameras, and in instruments intended to cover a wide field of view, the aperture stop is usually a material diaphragm behind the objective lens (in cameras with doublet lenses the aperture stop is placed between the two lens components).

It is interesting to note, as may be seen from fig. 49, that for a given position of the aperture stop, the larger the diaphragm opening, the smaller the fully-illuminated field of view. It is also interesting that if a diaphragm is used at a distance from the lens, the diameter of the lens must be greater for a given maximum size of effective aperture. It is the diaphragms of the system which dictate the required diameter of the lenses composing it, consequently the size and location of diaphragms in an optical instrument is a matter of considerable importance.

92. Effect of Aperture Stop on Field of View

We have seen that the field of view is controlled by the aperture stop, and becomes smaller as the aperture stop becomes larger. In the case where the lens itself serves as aperture stop, it is sometimes said that a change in the diameter of the lens has no effect on the field of view. This statement is more or less true, but not strictly so. In fig. 50, we see that if the diameter of the first lens is increased, the extreme rays passing the edge of the diaphragm at D′ will miss the edge of lens II, and consequently the diameter of the field stop DD′ will have to be decreased slightly. Lens I is the aperture stop for lens II, and, therefore, is subject to the general rule stated in the first sentence of this section. But this effect is slight if the distance of lens II from the image plane of the first lens is small with respect to the distance of lens I from it, as is usually the case, and the reduction in the size of the field of view will not be at all proportionate to the change in the diameter of the first lens; so that it is true, at least, that a change in the diameter of the first lens will affect the field of view only to a very small degree. However, a change in the diameter of lens II will affect the attainable field of view very materially.

93. Computation of Aperture and Field of View

The aperture and field of view corresponding to a given position and size of diaphragm can be easily calculated. If, in fig. 52a, we call the radius of the diaphragm opening A_1, the

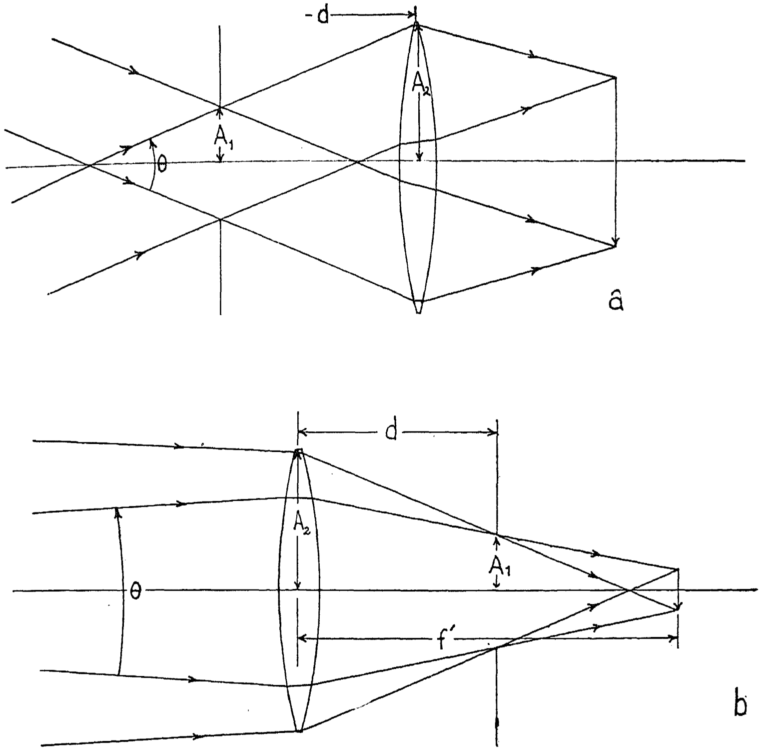

FIG. 52

Field of view of an optical system

radius of the aperture of the lens A_2, the distance of the diaphragm from the lens d, and the field of view θ, we have, when the diaphragm is in front of the lens:

$$\tan \frac{\theta}{2} = \frac{A_2 - A_1}{d} \tag{26}$$

When the diaphragm is behind the lens the focal length of the lens becomes involved in the determination of the field of view, and we have (appendix I, fig. 52b):

$$\tan \frac{}{2} = \frac{A_2}{f} + \frac{A_2 - A_1}{} \tag{26a}$$

Where two lenses are involved, the second being placed beyond the principal focus of the first, the problem becomes somewhat more complicated, as shown in fig. 53. If we use

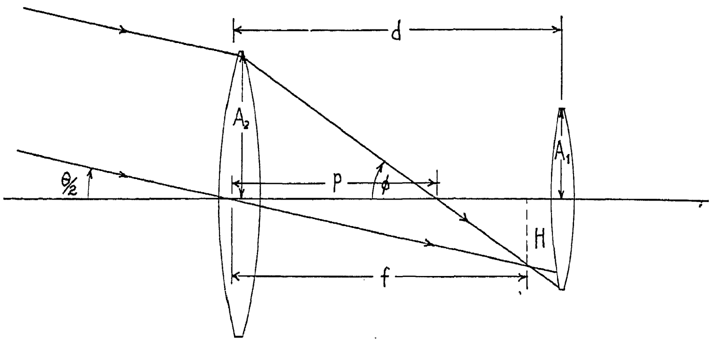

FIG. 53

Field of view of a system of two thin lenses

the same symbols as before, remembering that the second lens is the diaphragm for the first, and put A_1 for the radius of the second lens, A_2 for the radius of the first, and d for the distance between the lenses, f being the focal length of the first lens, we can write as follows (appendix I):

$$\tan \frac{\theta}{2} = \frac{f(A_1 + A_2) - A_2 d}{fd} \tag{26b}$$

where we know the aperture of both lenses and require the field of view.

If we know the aperture of one lens, and the specified field of view, and require the aperture of the other lens, we have:

$$A_1 = d \tan\frac{\theta}{2} + A_2\left(\frac{d}{f} - 1\right)$$

$$A_2 = \frac{fd \tan\frac{\;}{2} - A_1 f}{f - d} \tag{26c}$$

94. The Pupils of an Optical System

The effects of diaphragms on an optical system can most clearly be understood by a consideration of the *pupils* of the system. As was seen in the discussion of the case in fig. 51(b) and of the case in fig. 53, when the effective diaphragm is not located in the object-space, the problem of determining what points in the object-space can give rise to a bundle of rays which will pass exactly through the diaphragm is not purely a matter of inspection, as it is in the case of fig. 52(a). We are indebted to Abbé for a very systematic method for the discussion of such cases, which treats of the conditions with reference to the pupils of the system.

The name *pupil* is derived from the analogous case of the human eye. The eye is much like a camera, as we shall see in chapter XII, and its aperture stop is the iris, which contracts and expands to control the amount of light reaching the light-sensitive retina. As we look into the eye from its object-space we see a round black spot which we call the pupil. The pupil is not a material body, but a hole in the iris. But we do not see the actual opening in the iris because of the intervening refracting surfaces of the cornea. What we see is a virtual image of the opening in the iris.

Abbé defined the *entrance pupil* of an optical system as the aperture stop *as seen from the object-space.* If the actual diaphragm is situated in the object-space, it is the entrance pupil. If it is situated within the system, the entrance pupil is its image

as seen from the object-space (usually virtual). Conversely, the *exit pupil* is this aperture stop (or its image) *as seen from the image-space.*

If we now consider a system whose entrance and exit pupils have been determined, we can discuss its aperture and field of view without reference to the individual lenses contained within it. The exception must be noted that the *diameter* of the individual lenses must be computed separately by consideration of the conditions surrounding each lens. Fig. 54 shows a sample optical system, whose pupils have been determined. The entrance pupil is exhibited as a virtual image of a diaphragm located somewhere within the system, and the exit pupil as a real image (of the same diaphragm). We need draw for the system itself only the two principal planes.

Now, because the entrance pupil is an image of the actual

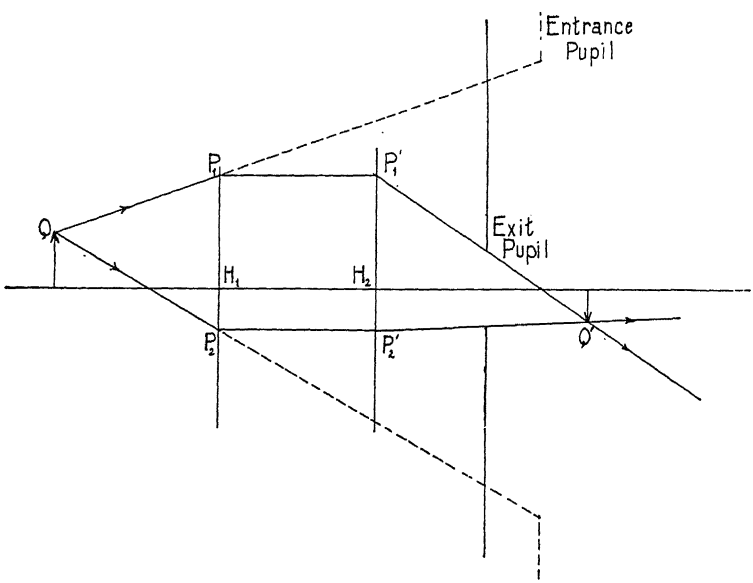

FIG. 54

Entrance and exit pupils of an optical system

diaphragm, any ray which passes a given point of the diaphragm (say the extreme edge) must pass through the corresponding point of its image, the entrance pupil, and a similar consideration applies to the exit pupil. And, since the entrance and exit pupils are two images of the same diaphragm, any ray which passes a given point of the entrance pupil must also pass the corresponding point of the exit pupil.

Therefore, for an object-point Q, the effective bundle of rays producing an image at Q′ is that bundle represented by the cone whose apex is Q and whose base is the entrance pupil. And this bundle must emerge from the system as represented by the cone whose apex is Q′ and whose base is the exit pupil. The knowledge that the rays piercing the primary principal plane at P_1 and P_2 must emerge from the secondary principal plane at P'_1 and P'_2 (whose distances from the principal axis are the same as the distances of P_1 and P_2), respectively, permits us to determine the image-point Q′ of a given object-point Q by purely graphical means without any definite knowledge about the interior of the system, except such as is necessary to determine the size and location of the pupils and the principal planes.

It is important to note that, although the pupils are symmetrical about the principal axis, we must know whether or not they are *inverted* with respect to each other, in order properly to draw in the entrant and emergent rays. In the case shown in fig. 54, it has been assumed that both pupils were of the same aspect, that is, either both erect or both inverted. If the exit pupil were inverted with respect to the entrance pupil, then the edge of the exit pupil corresponding to the edge of the entrance pupil which is below the axis in the diagram would be above the axis, and the two rays emerging from P'_1 and P'_2 would intersect above the axis and between the exit pupil and the secondary principal plane.

Any optical system divides all space into two parts, the object-space and the image-space. For every point in the object-

space there is a cone of rays for which there is a corresponding cone of rays in the image-space. The entrance pupil is the common base of all the cones of rays in the object-space and the exit pupil is the common base of all the cones of rays in the image-space.

CHAPTER XII

THE HUMAN EYE

95. Structure of the Eye

The optical system of the human eye is very much like that of a camera. There are two main optical systems, the cornea-aqueous humor combination, and the lens-vitreous humor combination, separated by a diaphragm, the iris (fig. 55).

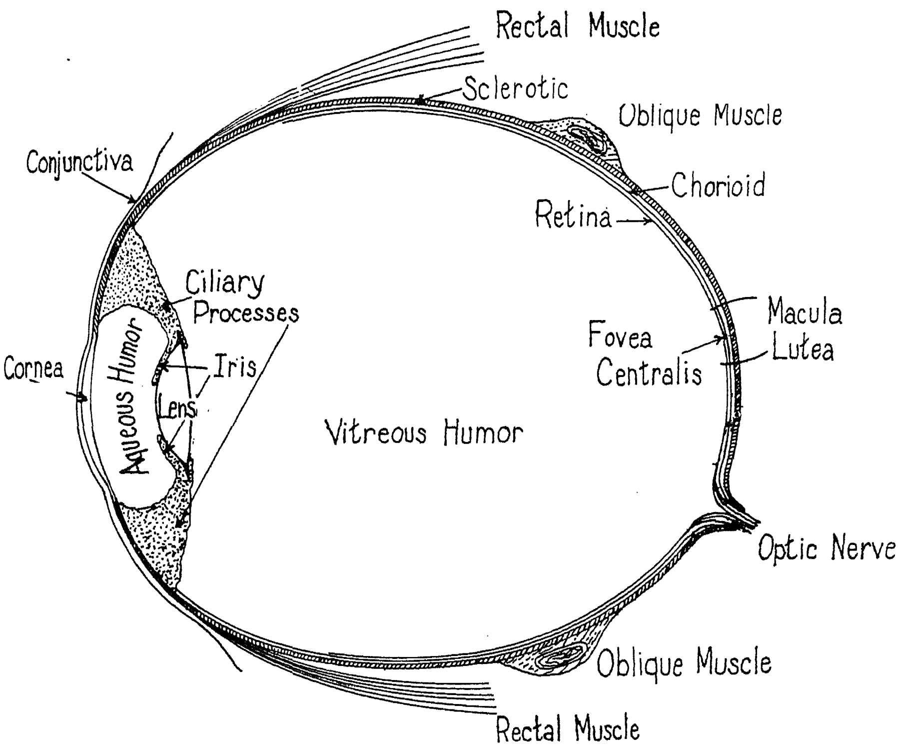

FIG. 55

Structure of the human eye

The *cornea* is a slightly bulging, transparent section of the *sclerotic* (which forms the eyeball), and constitutes a meniscus converging lens. Separating the cornea and the *lens* is the *aqueous humor,* a colorless liquid. The lens is double-convex, with a somewhat longer radius on the posterior surface. The remainder of the eyeball is filled with the *vitreous humor,* a jelly-like substance, very transparent, which maintains the shape of the eyeball. The interior of the eyeball is lined with the *retina,* the light-sensitive coating upon which the optical system of the eye forms a real, inverted image. Between the retina and the sclerotic is the *chorioid* coat, a thin, extremely black coating, and over the cornea is the very thin, transparent *conjunctiva,* which contains the nerve fibers that make the eye sensitive to dust, etc. There are capillaries in the sclerotic, but no nerve endings, and it is insensible to pain.

96. The Iris

Lying upon the anterior surface of the lens is an annulus of circular smooth muscle known as the *iris.* The pigmentation of the iris is responsible for the characteristic color of the eye, blue, brown, gray, etc. The muscles of the iris contract or dilate to regulate the effective aperture of the eye, and thus the amount of light permitted to reach the retina. The retina is extremely sensitive, and too bright an image upon it will cause pain or even permanent damage, as when one looks directly at the sun. Further, the retina will not operate satisfactorily if the image upon it is too bright. The iris, therefore, contracts to a very tiny opening when the illumination is intense, and expands when the illumination is poor.

This adjustment of the iris is a completely reflex action, and is not consciously controllable. The maximum range of this adjustment is from a diameter of about 0.02″ to about 0.30″, a difference of 225 times in the amount of light permitted to enter the eye. The average opening in the iris is about .20″. The pupil, of course, as stated in (94), is the

virtual image, as seen in the cornea-aqueous humor system, of the opening in the iris.

The center of rotation of the eye is the center about which the motor muscles of the eyeball (the *recti* and *oblique* muscles) rotate the eyeball.

97. Accommodation

The equivalent focal length of the eye, relaxed, is about 23 mm., and the normal position of the retina is at exactly this distance from the secondary principal plane. Thus the images of distant objects would be formed exactly upon the retina. And, as in any optical system, the images of nearby objects would be formed at a greater distance from the lens, and would, therefore, be formed *behind* the retina, and be out of focus upon it. In a camera this would be adjusted by changing the distance of the retina from the lens. In the human eye, however, the adjustment is achieved by altering the focal length of the lens.

This is accomplished by a set of muscles surrounding the lens, called the *ciliary* muscles. Contraction of these causes the lens to bulge, increasing the curvature of its surfaces and decreasing its focal length. Since the posterior surface of the lens is in contact with the vitreous humor, most of the change takes place on the anterior surface. This process of changing the focal length of the eye so that objects at varying distances may all be focused on the retina is known as *accommodation*. In a relaxed state, the normal eye is focused for infinity. The power of accommodation is sufficiently great in most eyes for objects at a distance of six to eight inches to be made clearly visible.

The distances for which the eye is focused when relaxed and when the power of accommodation has been exerted to its maximum are known as the *far point* and *near point* of the eye, respectively. At birth, the far point is at infinity and the near point about three inches away. With increase in age,

the near point begins to recede, that is, the power of accommodation begins to diminish, until at the age of 40, the near point is at about 10 inches. It continues to recede as age increases until at the age of about 65, it has become virtual, and is located about 100 inches behind the eye. In the meantime, the far point has also become virtual, beginning at the age of about 55, keeping always ahead of the near point however, and the eye will be unable to focus any object clearly. With even more advanced age, both points recede even farther, until by about the age of 75, both far and near points coincide at about 20 inches behind the eye, and the power of accommodation has been entirely lost. This loss of the power of accommodation, through the wearing out of the ciliary muscles or loss of elasticity of the lens or other causes, is such a universal and consistent occurrence that an oculist can make a very accurate guess as to an individual's age by measuring his power of accommodation.

The condition of lack of power of accommodation, always present with advanced age, but sometimes occurring as an abnormal condition at earlier ages, is known as *presbyopia* (old-age vision). This is considered to have set in when the near point has receded to a distance of 22 cm.

98. Ammetropia

The condition of the normal eye, when very distant objects focus clearly on the retina when the power of accommodation is completely relaxed, is known as *emmetropia*. When the far point does not lie at infinity, we have the condition of *ammetropia*.

Ammetropia may take either of two forms, *myopia* or *hyperopia,** near- or far-sightedness. In the myopic eye, the images of distant objects fall in front of the retina. Obviously, near objects will be focused at a greater distance from the

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* The strictly correct word is *hypermetropia*, but hyperopia is universally used in the ophthalmic trade.

lens, and for objects at a certain critical distance (the far point) the images will be clearly formed upon the retina. Myopia may be caused either by the length of the eyeball being too great or by a lens whose curvature is abnormally great. The former condition is the most common, the latter being rare.

The myopic eye has full power of accommodation. But its far point is not at infinity, but at a finite distance in front of the eye, and objects lying beyond this distance cannot be

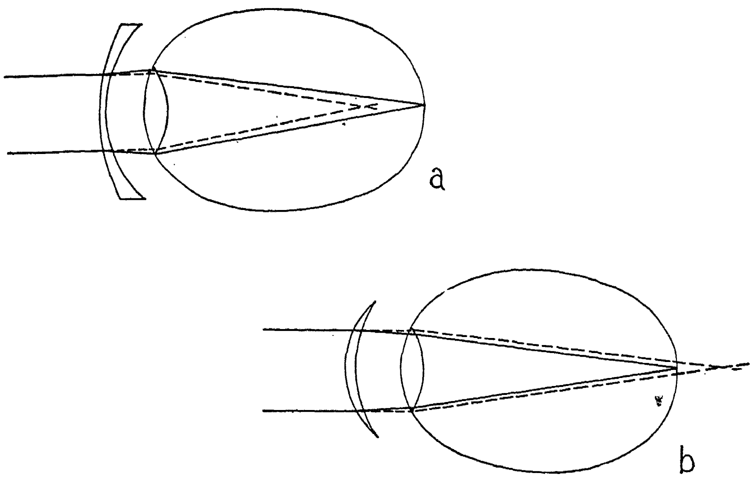


FIG. 56

Ammetropia

a. Myopia. b. Hypertropia.

brought to sharp focus on the retina, and consequently cannot be clearly seen (fig. 56a).

Hyperopia is the opposite condition, where the far point is virtual, and the near point much farther away than normal. In extreme cases, the near point may also be virtual, in which case nothing can be clearly seen. This may be due to an eyeball which is too short (most common), or to a lens having insufficient curvature (rare) (fig. 56b).

99. Correction of Ammetropia

Ammetropia is easily corrected with spectacles of such curvature that the far and near points of the normal eye are imaged at the far and near points of the ammetropic eye in question. This requires merely that the refracting power of the eye plus the spectacles be equal to the refracting power of the normal eye. It is easily seen how the conception of refracting power, as considered in (69), becomes useful in ophthalmic work.

In myopia, a diverging lens is required in the correction spectacles, and, conversely, a converging lens is required to correct hyperopia. Hyperopia is more common than myopia.

Correction spectacles are usually made in meniscus form, because of the great range of movement and large field of view of the eye. The distance of the spectacles from the eye will have an effect on the degree of correction, therefore it is advisable for the distance to be nearly the same for any direction of view. The only way to achieve this is to make the spectacles in meniscus form, concave to the eye.

In recent years *contact lenses* have come into common use to replace ordinary spectacles. These contact lenses are made in meniscus form, and fit snugly to the front surface of the eyeball. They are sufficiently large to fit under the eyelids, and are tinted to imitate the color of the iris, so that they are invisible to a casual glance. Once the wearer has become accustomed to them, they are not uncomfortable, and have the advantage of being protected from breakage and dirt in the same way that nature has protected the eye itself with the eyelids, eyelashes, and eyebrows. Optically, a contact lens is much more efficient than ordinary eyeglasses, although it is not possible to make it in *bifocal* form (fig. 57).

Bifocal spectacles are made of lenses of two different curvatures, so that they will compensate for two different object distances, the wearer looking through the upper part of the

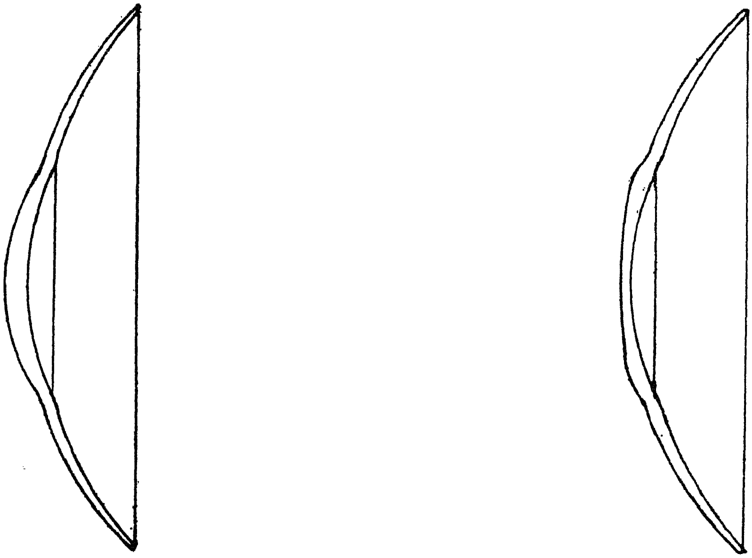


FIG. 57

Contact lenses

glasses at distant objects and through the lower part at close objects. Bifocals are of particular use in cases of presbyopia.

100. Astigmatism of the Eye

In (70) we mentioned toric lenses as lenses in which the radii of curvature are different in different planes. In such a lens, there is one plane where the curvature is greatest, and a plane, always perpendicular to the first, where the curvature is least. A toric surface is produced by the revolution of a circle about an axis which is parallel to a diameter of the circle but does not pass through its center (fig. 58).

In such a lens, the focal point for rays incident along a given plane will be different from the focal point for rays incident along another plane, and there will be two planes, perpendicular to each other, for which the focal length will be a maximum and a minimum.

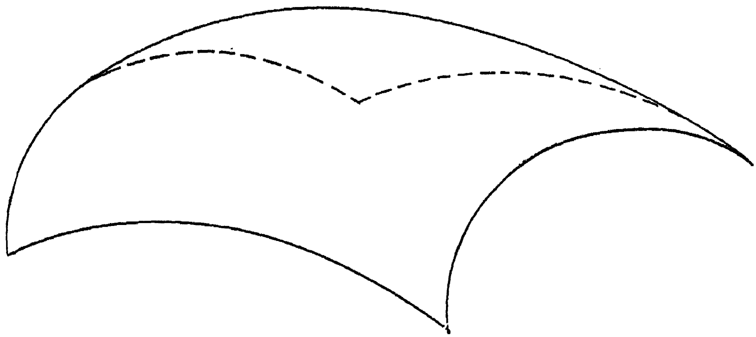


FIG. 58

Toric surface

It is frequently found that the human eye contains toric surfaces instead of spherical ones, and this gives rise to the condition known as astigmatism. The effect in the case of ordinary objects is merely poor definition, but it is pronounced in the case of objects which contain straight lines. Straight lines in one plane will require a different position of the retina than lines in another plane, and consequently a different degree of accommodation. Obviously, the eye cannot accommodate for two different image distances at the same time.

The remedy for astigmatism is, of course, the introduction of a toric spectacle lens (70) of such curvature that the asymmetry of the curvatures in the eye is compensated. In extreme cases, the spectacle lenses may be cylindrical, but they are usually meniscus toric lenses, for the same reason that lenses for correcting ammetropia are meniscus.

It has been found that, almost invariably, the astigmatism of the human eye is located in the cornea. It is extremely rare for the lens to be asymmetric, which is not surprising, for the elasticity of the lens would cause it automatically to assume a spherical form.

101. The Retina

The *retina,* although very thin (0.4 mm.) is a complicated structure, containing no less than 10 distinct layers. It is composed of neurone systems of two different types, named *rods* and *cones* from their geometrical form. The receptors of these neurone systems are located at the back of the retina, away from the optical system of the eye, and the light has to penetrate the entire retina before affecting the receptors. The *modus operandi* of the receptors is not yet clearly understood, but is known to involve the bleaching of dye substances in the rods and cones which is replenished during the periods when the eye is not being used.

Slightly above and outside the optical axis of the eye is a small area of the retina, known as the *macula lutea,* or yellow spot, where the neurones are very closely packed, and much more numerous than elsewhere in the eye. It is a common fact of experience that, although the field of view of the eye is extremely great (nearly 180°), the field of distinct vision is quite small (less than 1°). At the center of the macula is a tiny depression known as the *fovea centralis,* which is the region where the field of really distinct vision is focused, and which determines the line of fixation and the point of fixation. The point of fixation is the object-point toward which the eye is directed, and the line joining it with the fovea centralis is the line of fixation.

The exact functions of the rods and cones are not thoroughly understood, but it is fairly well confirmed that the cones are responsible for daylight vision, that is, when the illumination is reasonably great, and that the rods are responsible for twilight vision, that is, when the illumination is feeble. This belief is borne out by the easily observed fact that objects in feeble illumination are most distinctly seen, not along the line of fixation, but at one side or the other of it, and that in darkness, things are frequently seen "out of the corner of

the eye" when they cannot be seen by direct vision. This is particularly true of faint stars in the field of an astronomical telescope, which are frequently seen by averted vision when direct concentration upon the spot where they are located will not disclose them. Now, the rods are much more numerous as we proceed away from the macula, very few rods being present in the macula itself, and none at all in the fovea centralis, and no cones at all are present at the extreme edges of the retina.

It is also a fairly well confirmed fact that color vision is possible only with the cones, for it is known that twilight vision is vision in black and white, and that it is almost impossible to distinguish colors under feeble illumination. The illumination, however, cannot have any direct effect upon the color of an object, so that it must be caused by a difference in the perception mechanism of the eye.

The point where the neurone connections of the retina merge into the great trunk of the optic nerve and leave the eyeball is known as the blind spot of the eye. It is located a little to the inside of the center of the retina, and it covers an area of about 6° x 8°, sufficient to contain the images of about 11 full moons.

102. Stereoscopic Vision

Because we have two eyes, which are separated by a distance of about 2½ inches (58–72 mm.), the two images of a given object on the two retinas occur in slightly different positions, unless the object is at a very great distance. These two slightly different fields of view are combined by the brain into a single *image in relief,* by means of which we can not only judge the direction of an object, but also its distance and real size as compared with other objects in the field of view.

Quite obviously, this *stereoscopic power,* or *stereopsis,* decreases rapidly with increasing distance, until it finally fades out altogether, commonly accepted as occurring at the distance

where the separation of the eyes subtends an angle of 30 seconds, or at about 500 yards. The stereoscopic power becomes greater as the distance to the object decreases, because of the rapidly increasing convergence angle of the two lines of sight.

If our eyes were farther apart, we could distinguish depth much more clearly; our stereoscopic power would be increased, and the *radius of stereoscopic vision* would be increased also. This is the function of binocular instruments, such as prism binoculars, which are so constructed that the objectives of the two telescopes (one for each eye) are separated by a distance greater than the separation of the eyes. Further discussions of this topic will be found in chapter XX.

CHAPTER XIII

Aberrations of Lenses

103. Introduction

In our previous discussion of lenses, restriction to paraxial rays (42) led us to two important and simplifying conclusions: 1) that all rays from a given object-point meet at its conjugate image-point and 2) that the image of a line perpendicular to the optical axis is also a line perendicular to the optical axis. We pointed out at that time that these conclusions are true only for paraxial rays, and it is our purpose in this chapter to investigate the phenomena of image formation without restricting our discussion to paraxial rays.

It is not our purpose to develop equations for imagery without the restrictions implied by paraxial rays, but only to investigate the *departure* of the true imagery from the *ideal* imagery represented by the paraxial results. We shall, therefore, be interested in two phases of difference in image-points formed by rays incident over the entire aperture of a system of finite aperture, the *character* and the *location* of the image-points.

Any difference between the image-point actually formed by an optical system operating at finite aperture and the image-point theoretically formed by the same system at the zero aperture assumed by the paraxial condition is termed an *aberration* of the system. It is important to realize at the outset that an aberration is the result of the inapplicability of the paraxial conditions to actual optical systems, and not the result of improper manufacture of the optical elements comprising a system. Improper manufacture will introduce difficulties with

the imagery, it is true, but *aberrations* are what might be called natural faults of refracting and reflecting surfaces.

There are seven different ways in which an optical system can fail to produce the image called for by the paraxial considerations, and these are the seven aberrations: *axial* and *transverse chromatic aberration, spherical aberration, distortion, astigmatism, coma,* and *curvature of field.*

CHROMATIC ABERRATION

104. Dispersion

We begin by discussing an aberration which is present even in paraxial imagery, and which is due, not to the character of the optical system, but to the nature of light. We stated in (5) that different colors of light represented different wave-lengths, also that the velocity of light in material media is different for different wave lengths, being always greatest for the red and least for the violet. This leads at once to the conclusion that the index of refraction of a given medium is not a constant, but varies with the wave-length of the light concerned, and, since the index of refraction determines the focal length of a lens or refracting surface (49), the focal length will not be constant, but will vary for different colors of light.

The action of a refracting surface or surfaces in separating a beam of light into its component colors or wave lengths is known as *dispersion,* and is best exemplified by a prism, as shown in fig 59. The velocity of the red light being greatest in the prism, it is bent least, both upon incidence and emergence, the bending being greatest for the violet. Consequently the paths of the different colors of light emerging from the prism are different, and a screen placed in the path of these rays will show a band of color, ranging from red through yellow, green, blue and violet, known as the *visible spectrum.* As will be seen in chapter XXII, this phenomenon is of immeasurable value in

analyzing light, but it is evident that its presence in ordinary optical systems is extremely undesirable.

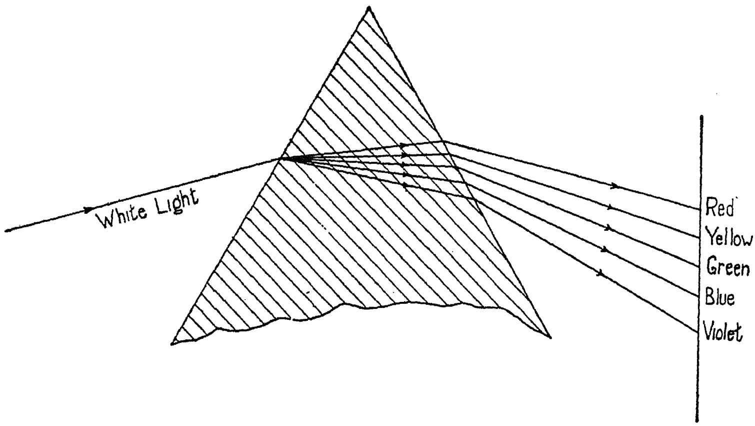


FIG. 59

Dispersion by a prism

If a prism similar to that in fig. 59 is placed in the path of light from a lens which is forming an image of a narrow illuminated slit, whose plane is perpendicular to the plane of the paper in the diagram, the effect of the prism will be to form innumerable overlapping images of this slit, thus building up the band known as the spectrum. A single image of such a slit, corresponding to a particular wave-length of light, is known as a *spectral line*. Certain spectral lines are indicated by letters, such as D, F, C, etc. (See chapter XXII.)

105. Chromatic Aberration

The aberration caused by dispersion in an optical system is known as *chromatic aberration*. It is defined for a paraxial image-point, and numerically it is equal to the distance along the optical axis between the image-points formed by the light of two given wave-lengths. Since the value of this distance will vary with the distance of the object-point whose image is

being formed, it is desirable to define the aberration more precisely by restricting the definition to incident parallel light, that is, light emanating from an object-point at infinity.

In fig. 60, let C be the chromatic aberration, or difference between f'_C and f'_F, red and violet light, respectively. We have, then:

$$\frac{1}{f'_C} = (N_C - 1)\,c \qquad\qquad \frac{1}{f'_F} = (N_F - 1)\,c$$

therefore (appendix I):

$$C = f'_C - f'_F = \frac{f'}{V} \tag{27}$$

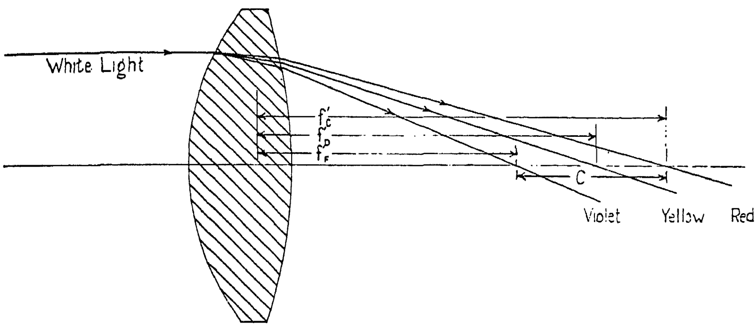


FIG. 60

Chromatic aberration

Here, we have taken the two wave-lengths represented by the C and F spectral lines (see chapter XXXIII) at wavelengths 6563 Å and 4861 Å, respectively, in accordance with common practice, and have put f' without subscript as the focal length for the D-line of the spectrum, at 5893 Å. The value V is equal to $\frac{N_D - 1}{N_F - N_C}$, where N_D, N_F, and N_C are the refrac-

tive indices for the spectral lines corresponding to the subscript letters.

The quantity C will be positive if N_F is greater than N_C provided that f′ is positive, which is always true, since N is the ratio of velocities of the light in air to the light in the lens, and the velocity of violet light in glass is always less than that of red light. When f′ is negative, for a diverging lens, C will also be negative. Therefore, we see that the chromatic aberration has a positive sign if the red focus lies to the right of the violet focus and a negative sign if the positions of the two foci are reversed. In any case, the violet focus will lie nearer to the lens.

Since C varies directly as f′, it varies directly as the radii of the surfaces, and becomes greater as the focal length increases. Thus it might seem that lenses of short focal length suffer less from chromatic aberration than those of longer focal length. So far as concerns the numerical measure we have just developed, this is true, but the *longitudinal chromatic aberration* defined above is not at all an equitable measure of the seriousness of the aberration from the standpoint of definition of an image-point. A truer measure is the *angular aberration*, or difference of convergence angles of the various rays. A very commonly used criterion is the difference in the optical paths of the various rays (6).

It was stated by Lord Rayleigh in 1878 that the image of a point would not differ sensibly from a perfect image if the optical paths of the rays composing it did not differ from one another by more than one-quarter of a wave-length. This is known as the *Rayleigh limit*, and, while it has never been mathematically proved, principally because of lack of any suitable numerical measure of the perfection of an image-point, searching tests have failed to disclose any cases where it cannot be regarded as strictly true.

If we accept the Rayleigh limit, the seriousness of chromatic aberration for a given aperture varies *inversely* with the

length of an optical system, and for a single lens the minimum focal length required to reduce the chromatic aberration to the limit is:

$$f'_o = 100\,A^2 \tag{28}$$

where A is the aperture in inches.

This equation explains why, in the early days of astronomical telescopes, they were built with fantastically long focal lengths. Telescopes with objectives of four to five inches aperture were made 100 and 200 feet in length, and there is a record of a telescope of 300-foot focal length having been manufactured, although there is no record of its having been used.

106. Achromatism

Sir Isaac Newton worked on this problem of chromatic aberration and dispersion, and arrived at the conclusion that the dispersion of two refracting media (the difference between the refractive indices for two selected colors) was proportional to the mean refractive index, and consequently there was nothing that could be done to correct the fault of chromatic aberration. Thus convinced, he gave up the refracting telescope and turned his attention to the reflector.

Fortunately for the optical industry, he was wrong. The dispersions of two refracting media are not linearly proportional to their mean refractive indices. If medium A has an index of refraction (for the D-line) twice as great as that of medium B, the dispersion of medium A will usually be greater than that of B, but not exactly twice as great.

About 1760 John Dollond (or C. M. Hall, opinion is divided as to where the credit belongs), in England, realized that this circumstance made it possible to produce a lens which would be free of chromatic aberration by combining two different kinds of glass whose dispersion was different. If we combine a converging lens of a certain kind of glass with a diverging lens of a kind of glass whose dispersion is greater, then the

curvature required in the second lens to compensate for the chromatic aberration of the first will not be as great as the total curvature of the first lens, and the resulting combination will have a net positive curvature. If the dispersions were linearly proportional to the mean indices of refraction, the focal length of the second lens would be equal and opposite to that of the first and the combination would act like a plane-parallel plate. But, since the dispersions are not linearly proportional to the indices, it is possible to produce a lens of this sort with a definite positive (or negative) focal length. Such a lens is called an *achromatic* lens (fig. 61).

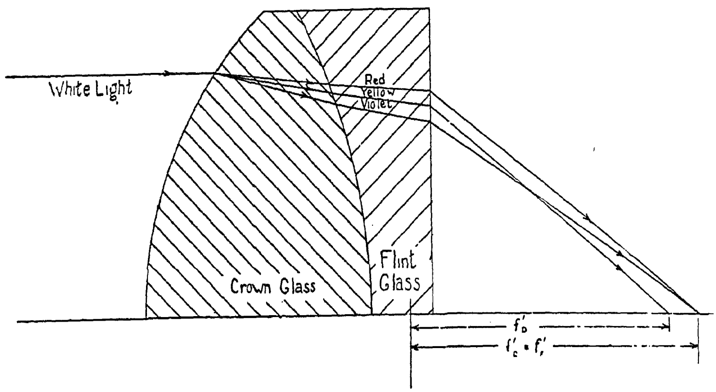


FIG. 61

Achromatic lens

The ratio of focal length of the two components (appendix I) is:

$$\frac{f'_2}{f'_1} = -\frac{V_1}{V_2} \qquad (29)$$

or inversely as the V-value of the two different glasses. This is the reason for selecting the particular function for the dispersion indicated by V.

If the chromatic aberration of a lens or system has not been

completely removed, that is, if there is a residual of positive chromatic aberration, the system is said to be *undercorrected;* conversely, if there is a residual of negative chromatic aberration, the system is said to be *overcorrected.*

107. The Characteristics of Optical Glass

There are two principal types of optical glass: crown and flint. Crown glass forms the converging, low-dispersion element of converging achromatic lenses, while flint glass is glass of high dispersion, and forms the diverging element of these lenses. There are many varieties of each type, with varying characteristics.

Catalogues of optical glass list the refractive indices for several different wave-lengths, the dispersion ($N_F - N_C$), and the V-value. It is evident from the form of the function giving the V-value (105) that a glass of high dispersion will have a low numerical V-value. A list of representative glasses, offered by the Bausch & Lomb Optical Co., follows.

Type	N_D	V	$N_F - N_C$	N_F	N_C	$N_{G'}$
BSC-1	1.5110	63.5	0.00805	1.5167	1.5086	1.5211
C-1	1.5230	58.6	0.00893	1.5293	1.5204	1.5344
LBC-1	1.5411	59.9	0.00904	1.5475	1.5384	1.5526
DBC-1	1.6110	58.8	0.01039	1.6183	1.6079	1.6242
ELF-1	1.5585	45.5	0.01227	1.5672	1.5550	1.5745
BF-1	1.5838	46.0	0.01269	1.5928	1.5801	1.6003
LF-1	1.5725	42.5	0.01347	1.5821	1.5686	1.5901
DF-1	1.6050	38.0	0.01595	1.6164	1.6004	1.6260
EDF-3	1.7200	29.3	0.02457	1.7377	1.7131	1.7530

It will be noted that the range of indices of refraction is only about 0.20, or 14%, while the range of $N_F - N_C$ is about 0.016, or 200%. The initials indicate: BSC—Borosilicate Crown; C—Ordinary Crown; LBC—Light Barium Crown; DBC—Dense Barium Crown; ELF—Extra Light Flint; BF—Barium Flint; LF—Light Flint; DF—Dense Flint; EDF—Extra Dense Flint. The above are only a few of the available glasses, there is a long list of others, and many with very speciai

properties. The only glass listed in the above table which is really a special glass is the dense barium crown. It will be noted that the index of refraction for this glass is greater than that for any of the flints except the last one, but that the dispersion is true to form for a crown glass. This glass finds its principal use in the eye lens of Kellner eyepieces (see 134) and in camera lenses. A fuller discussion of optical glass and its properties will be found in chapter XXXII.

Any crown-flint pair from the above table can be made into an achromatic lens; the actual selection of glass for a proposed design is based upon many considerations, of which the possibility of chromatic correction is only one.

108. Focal Lengths of Achromatic Lenses

Equations (27) and (29) were expressed in terms of the V-values of the glasses concerned, and the V-values were expressed in terms of the indices of refraction for the C and F spectral lines. It would be possible to compute a V-value for any other pair of wave-lengths, which would be different from the V-value obtained for C and F. The ratio $\frac{V_1}{V_2}$ which determines the relative curvatures of the two components of the achromatic lens would be different if the V-values were computed for a different pair of wave-lengths.

The result is that colors other than C and F will not be brought to the combined CF focus of the lens, but will be spread out along the optical axis. They will, however, focus in pairs; and the entire spread of the spectrum will be less than it would have been were the lens uncorrected for chromatic aberration. The spread of colors remaining in the achromatic lens is known as the *secondary spectrum*. If the focal length for an achromatic lens is plotted as ordinate against the wave-length as abscissa, a parabolic curve is obtained, similar to those in fig. 62.

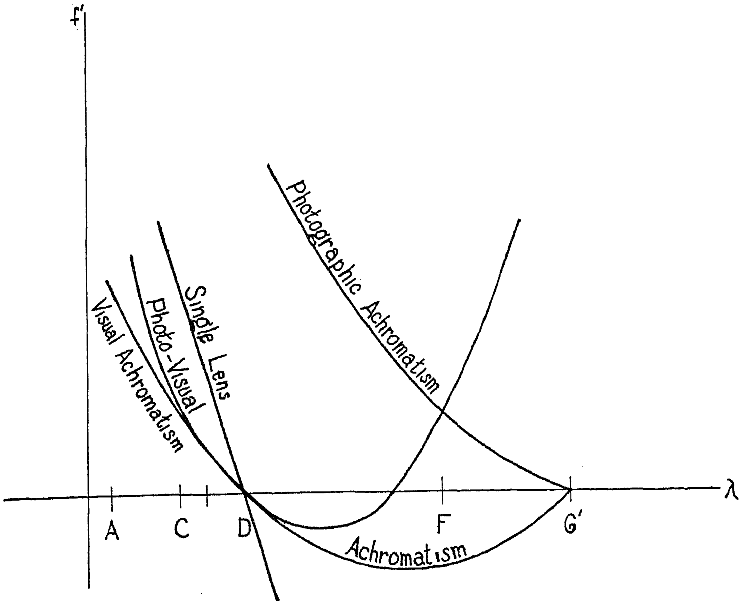


FIG. 62

Focal lengths of an achromatic lens

109. Types of Achromatism

The significant fact about the curves in fig. 62 is the position of the vertices of the curves. This represents the *minimum focal length,* and in its vicinity, the range of focal length is small for a rather wide range of wave-lengths.

If achromatism is established for a pair of wave-lengths other than C and F, the position (with respect to wave-length) of this minimum focus will change, and it is the position of this minimum focus which determines the *type* of achromatism present.

It is the aim of the optical designer to establish the minimum focus in the region of *brightest light,* the light which the particular instrument in question can use most effectively. In an

instrument to be used visually, this is in the yellow-green region of the spectrum, because the eye is most sensitive to yellow-green light. The establishment of achromatism for the C and F lines brings the minimum focus to a point somewhat below the bright yellow D-line, which explains the selection of C and F as the basis of the V-values given in glass catalogs. In the case of a photographic instrument, the brightest light is in the blue (where the photographic plate is most sensitive) and this calls for the selection of a different pair of wave-lengths (usually D and G′) to bring the minimum focus into the blue region.

SPHERICAL ABERRATION

110. Refraction at a Spherical Surface

If we refer back to fig. 25, and determine the numerical relationships without restriction to paraxial rays, we obtain (using upper-case letters to distinguish relations which are not paraxial), according to our conventions in (32), (appendix I):

$$
\begin{aligned}
n \sin I &= n' \sin I' \\
\sin I &= \frac{(M - r)\sin U}{r} \\
U' &= U + I - I' \\
M' &= \frac{r \sin I'}{\sin U'} + r
\end{aligned}
\qquad (30)
$$

The equations are the same as those given in (48) with u replaced by sin U, except the equation for U′. Because U′ is not the sum of the sines of U, I, and I′, but the sum of the angles themselves, M′ is not independent of U except for angles whose sines may be put equal to the angles themselves, that is, for paraxial angles. Consequently we may expect M′ to be different for different values of U, and this means that all the rays emerging from an object-point will not meet at an image-point, but will cross the axis at various distances from the lens.

In general, the ray passing through the lens farthest from the principal axis will cross the axis nearest to the lens, as shown in fig. 63. The separation of the focus for the rays farthest from the axis (marginal rays) from the *ideal* focus

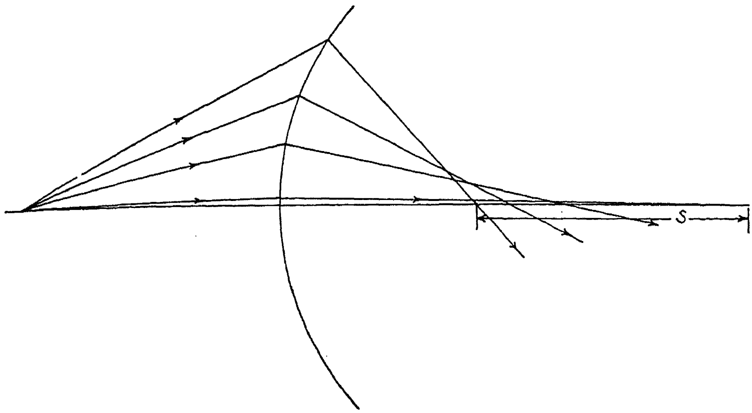


FIG. 63

Spherical aberration

for the paraxial rays is the *spherical aberration.* It is defined as the paraxial focal length minus the marginal focal length, and is positive for a converging lens, negative for a diverging lens. It grows as the square of the aperture.

111. Spherically Corrected Lenses

The spherical aberration may be treated surface by surface through a system, and, since surfaces with positive curvature give positive spherical aberration and surfaces with negative curvature give negative spherical aberration, it is possible to adjust the relative curvatures of the surfaces involved so that the spherical aberration shall be zero for the combination.

It is also possible to eliminate the spherical aberration in an achromatic lens, and still retain the ratio of total curvatures of the two elements required for chromatic correction. For,

although the condition for achromatism and the required focal length completely define the total curvatures of the two elements, they put no restrictions upon the *distribution* of the total curvatures over the two surfaces of each element, and thus an infinite number of lenses are possible with a given pair of glasses. This leaves the distribution of the curvatures available for the correction of spherical aberration (381). The process of redistributing the curvatures of such a lens without changing the total curvature is known as *bending* a lens (fig. 64).

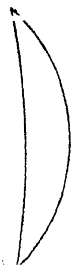


FIG. 64

"Bending" a lens

All the above lenses have the same total curvature and focal length, but different values of the spherical aberration.

If the lens is to be cemented, the curvatures of the two inside surfaces must be equal; this reduces the number of possible solutions for zero spherical aberration to two, one of which is generally unsuitable by reason of being affected by other aberrations, to be discussed below. If the two components of the lens are separated, however, the curvatures of the two inside surfaces need not be the same, and there are an infinite number of spherically corrected solutions. Fig. 65 shows some of the more common forms of *broken-contact* achromatic lenses.

As in the case of chromatic aberration, the terms undercorrection and overcorrection are used to describe lenses which have residuals of spherical aberration positive and negative, respectively.

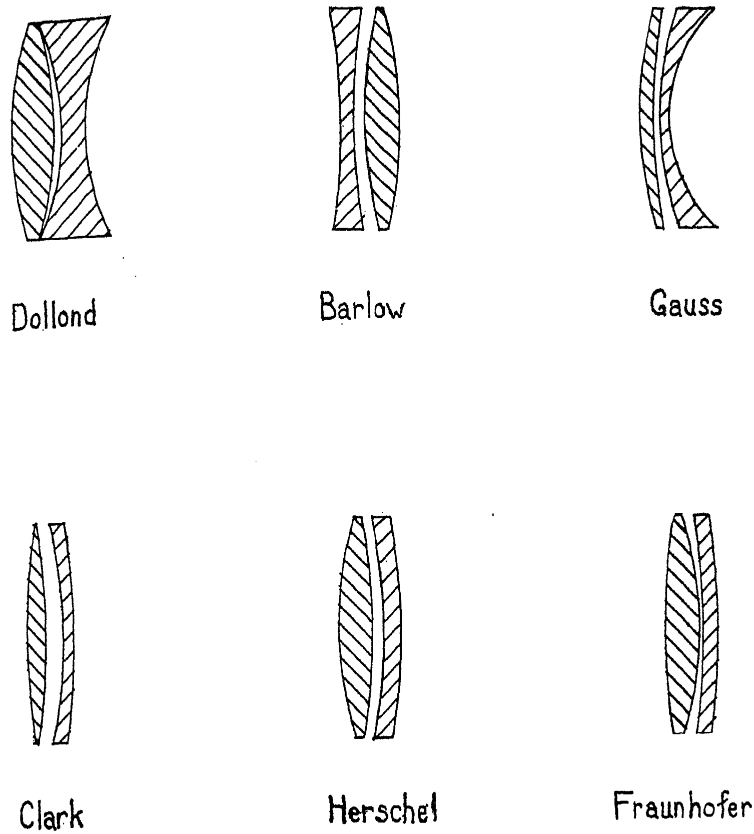


FIG. 65

Some common types of "broken-contact" achromatic lenses

112. Apochromatic Lenses

In cases where the secondary spectrum must be removed (lenses for color photography, etc.), the correction of chromatic aberration for two selected wave-lengths is not sufficient, and correction must be established for at least three separate wave-lengths. By using special glasses, Abbé was able to design two-component lenses which were *apochromatic,* corrected for three

colors; but due to the cost, instability and general unsuitability of these special glasses, two-component apochromatic lenses are rare. It is more common to achieve the apochromatic condition by the use of a combination of three different kinds of glass, and even this solution leads to steep and difficult curves.

113. Secondary Spherical Aberration

Bringing together the marginal and the paraxial rays at a single focal point does not automatically bring all other rays to the same point. The residual spherical aberration caused by the failure of rays from other zones than the marginal and the paraxial to meet at the spherically corrected image-point is called secondary spherical aberration. As is true of all the secondary aberrations, secondary spherical aberration is usually quite small, and negligible in ordinary cases. But in systems which require an extremely high state of correction, it must be taken into account, and eliminated. Indeed, it is the high secondary aberrations of large-diameter astronomical lenses which make them inferior to reflecting telescopes for most work.

ABERRATIONS OF OBLIQUE PENCILS

114. Extra-Axial Image-Points

Reference to fig. 49 will show that the effect of a diaphragm is to cause the bundles of rays from extra-axial object-points to pass through a different part of the lens than is the case for the axial bundle, and it should not be surprising if the state of the aberrations for these extra-axial points is quite different from that of the axial points, even when chromatic and spherical aberration have been eliminated for image-points on the principal axis.

In particular, if we draw an *auxiliary* optical axis (fig. 66) through an extra-axial object-point Q and the center of curvature of a refracting or reflecting surface (as we did in 53), we see that the rays from Q will exhibit spherical aberration

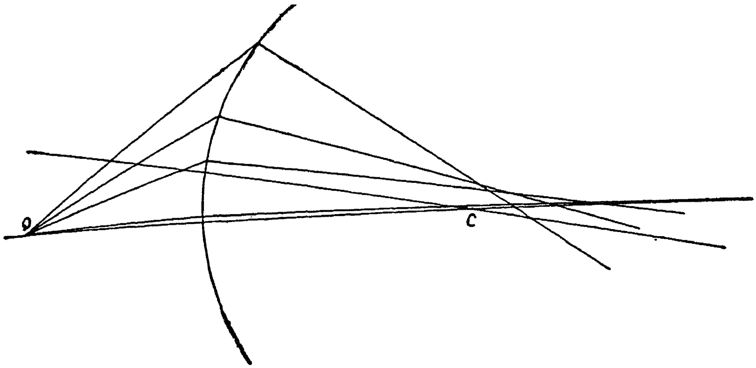


FIG. 66

Spherical aberration of an oblique bundle

with respect to the *auxiliary* axis in the same way as did the rays of the axial bundle with respect to the principal axis. But now the amount of spherical aberration present will be determined by the height of the ray above the auxiliary axis, and in general this will be considerably greater than the height of the rays of the axial bundle above the principal axis.

115. Distribution of the Focal Points for an Oblique Bundle

Fig. 67 shows a bundle of oblique rays emerging from the last surface of an optical system. The end view at the left shows the distribution of the selected rays around the chief ray. The rays come to focus in pairs from opposite sides of the perpendicular M_aM_b, and these foci are distributed on a short straight line known as the *characteristic focal line.* It must be realized that the figure shows a more-or-less idealized condition, where only rays around the periphery of the bundle are considered, and furthermore that the diagram represents a tremendous enlargement of the actual conditions. It must not be thought, however, that the characteristic focal line is a mathe-

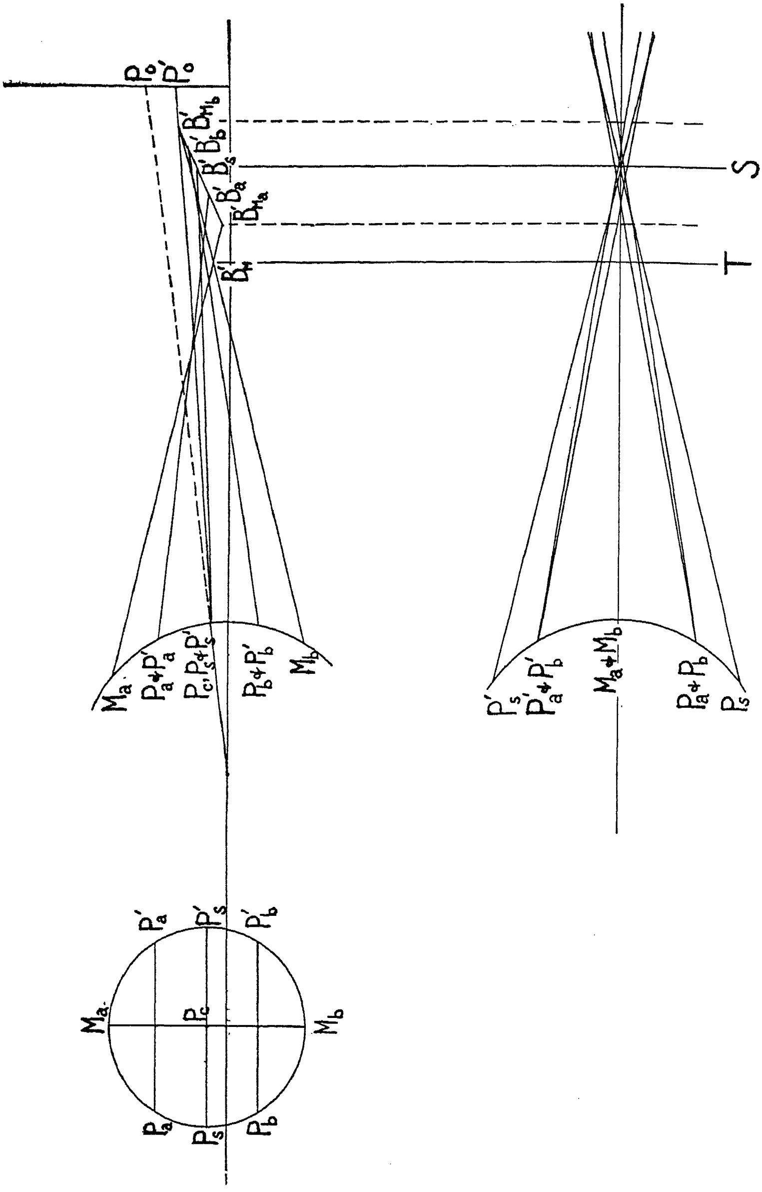


FIG. 67
Aberrations of an oblique pencil

matical fiction, for it is a very real phenomenon, and can be easily demonstrated on an optical bench.

116. The Tangential and Sagittal Foci

The rays lying in the plane defined by the perpendicular line M_aM_b and the chief ray are called the *tangential* rays, and those lying in the plane defined by the line $P_sP'_s$ and the chief ray are called the *sagittal* rays. The *tangential* focus occurs at the point where the rays from M_a and M_b intersect, and is indicated by the vertical projection line T in the diagram. The *sagittal focus* is the point where the rays from P_s and P'_s intersect in the center of the characteristic focal line, and is indicated by the vertical projection line S. The diagram in the upper right of fig. 67 may be considered an elevation and that in the lower right a plan. Considered together, these two aspects indicate that there are, in general, two constrictions of the rays in the oblique bundle, occurring at T and S respectively, a constriction in elevation occurring at T, and a constriction in plan occurring at S.

It will be seen that the image of an extra-axial object-point is, therefore, a more or less confused bundle of rays without any point focus, but with only regions of more or less constriction in different planes. Somewhere between T and S will be found the *best focus,* or point where the confused patch of light has the least cross-sectional area.

It can be seen from the diagram that if the aperture is reduced, the area covered by the confusion of rays will be reduced also, until at the limit, when the bundle has been restricted to the chief ray itself ($P_cP'_o$ in the diagram), it has been reduced to zero.

117. The Oblique Aberrations

The ideal image-point of the extra-axial object-point in question, whose location is given by the theorem of Lagrange (75, equation 18a), is at P_o. The Seidel aberrations, so-called

because they were first defined by Baron Ludwig von Seidel in 1857, arise from the various ways in which the rays in question fail to form a point image at P_o.*

A. Distortion

The dislocation of the chief ray, ($P_oP'_o$) from the ideal image-point P_o, is the *distortion.* If the ideal image-point lies farther from the axis than the actual image-point, as shown in fig. 67, the distortion is considered positive, and gives rise to a representation of the object in which the extra-axial image-points are too close to the center. If the distortion is negative, the image-points are spread away from the center. The two types of distortion are illustrated in fig. 68, which is the image of a square grid as produced by a lens affected with the type

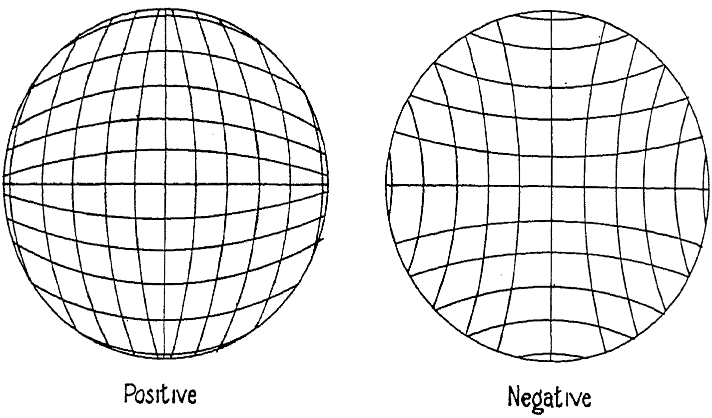


FIG. 68

Types of distortion

of distortion indicated. It is evident that distortion will persist in an optical system even if the aperture is closed to the extent of admitting only the chief ray, while all other aberrations

* There are six Seidel aberrations, corresponding to Seidel's six sums, but one of these is axial spherical aberration, and not properly included in a discussion of the oblique aberrations.

shrink to zero for this case. The same lens may give both positive and negative distortion, depending upon the position of the object-point, as may be observed in a positive lens used as a magnifier. In this case, the distortion is positive for object distances greater than f, and negative for object distances less than f. Distortion grows as the cube of the distance of the object-point from the principal axis.

B. Astigmatism

If the characteristic focal line were perpendicular to the optical axis, there would be complete constriction at T and S in their respective planes, and the image would be a sharp horizontal (tangential) line at T, a sharp vertical (sagittal) line at S, and a circle, called the *circle of least confusion,* mid-way between. This represents pure *astigmatism.* Astigmatism grows as the square of the distance of the object-point from the principal axis and directly as the aperture.

C. Coma

Coma is the irregular shape of the image area, and is the most objectionable of the oblique aberrations. It is evident that pure astigmatism is perfectly symmetrical about the chief ray, and even a badly astigmatic image can be bisected by cross-hairs, and reasonably accurate measurements made, but in the case of a comatic image, there is no indication where the center should be. Coma is represented in fig 67 by the distance of the tangential and sagittal foci from the chief ray. Coma gives rise to a comet-shaped image area, hence its name. It grows as the square of the aperture and directly as the distance of the object-point from the principal axis.

D. Curvature of the Field

If the positions of the tangential and saggital foci are plotted for object-points at different obliquity, they will lie on curved surfaces, of which the tangential focal surface will almost al-

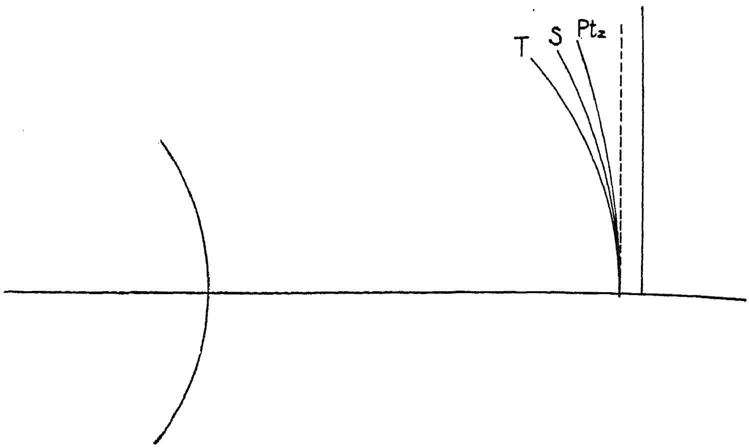


FIG. 69

Focal surface

ways have the greatest curvature (fig. 69). If astigmatism were absent, the tangential and sagittal foci would coincide, and the image-points would lie on a surface known as the Petzval surface, also shown in fig. 69. Curvature of the field is usually defined as the curvature of this Petzval surface. Unlike the other oblique aberrations, curvature of the field must be corrected by the use of the proper glasses in the system, since it is practically unaffected by changes in the curvatures or the thicknesses of the component lenses.

118. Transverse Chromatic Aberration

In addition to the five Seidel oblique aberrations, we have the aberration known as *transverse chromatic aberration,* resulting in a variation of magnification with the wave-length of the light. Its effect is to produce tiny spectra arranged radially to the principal axis. This aberration is present even when a system has been chromatically corrected for axial points. The removal of it is usually referred to as achromatism of magnification.

119. The Optical Sine Condition

A principle of great utility in optical design, first clearly stated by Abbé, is the *optical sine condition.* It represents a generalization of the theorem of Lagrange to include conditions of finite aperature. It may be stated in the form

$$y' n' \sin U' = y n \sin U \tag{31}$$

where y and y′ are the object and image heights, n and n′ the indices of refraction of the first and last media, and U and U′ the convergence angles in the object and image space, respectively.

The optical sine condition is necessary and sufficient for freedom of an optical system from coma, and it furnishes a very significant test of the conditions with respect to the other oblique aberrations, although it is not, as is sometimes erroneously stated, a rigorous measure of the state of perfection of image-points with respect to *all* the oblique aberrations.

DISCUSSION

120. Corrected Optical Systems

From the discussion on the preceding pages, it will be realized that the difficulties confronting the optical designer, in the production of a system of finite aperture which is to be reasonably free from image defects, are not to be taken lightly. A corrected optical system must satisfy no less than seven separate conditions, corresponding to the seven aberrations we have mentioned. This does not take into account nine varieties of higher aberrations, and five chromatic variations of the Seidel aberrations, which have never yet been set up in generalized mathematical form.

It may even be considered remarkable that it is possible to produce any optical system which will give reasonably good

definition. Fortunately, the situation is not quite as serious as it would seem at first glance. The aberrations are interdependent and correction for one may minimize others. Occasionally, however, this interdependence is a disadvantage. The important thing for the optical designer is that there be enough variables (enough different surfaces and kinds of glass, usually) to work with. It has already been shown that bending will not affect either chromatic aberration or curvature, but that correction for these aberrations must be achieved through the judicious use of glasses, which, in turn, have practically no effect on spherical aberration. Changing the position and aperture of the diaphragm is an effective method of controlling most of the oblique aberrations.

From the variation of the oblique aberrations with the distance of the object-point from the principal axis and with the aperture, it can be seen that it is only in the case of systems with a wide field of view and/or large aperture that the oblique aberrations really become troublesome. These conditions are particularly prevalent in cameras, and readily explain why good camera lenses are expensive. Most telescopic systems have a rather small field of view, and a rather small aperture with respect to focal length, and are not greatly troubled by the aberrations of extra-axial image-points.

It may be noted here that it is absolutely impossible to correct an optical system for all aberrations for more than one specified object distance. It might seem that this would eliminate the possibility of any *depth of field* (range of object distances for which sharp definition can be attained), but we must remember that it is not necessary that all aberrations be *completely* removed, only that they be reduced to tolerable proportions. Therefore, it is only because of *optical tolerances* that it is possible to attain any depth of field in optical instruments, our tolerances being usually dictated by the Rayleigh limit (105).

The theory of aberrations has not been discussed mathematically in this chapter. Such a discussion would require

a volume in itself, much larger than the present one, so no effort has been made to offer proofs, even in the appendix, for the propositions stated in the preceding few sections.

CHAPTER XIV

Erecting Systems

121. The Simple Telescope

It was mentioned in (78) that when $d = f'_1 + f'_2$ in a combination of two optical systems, the result is an *afocal* or *telescopic* system. The simple telescope is the most elementary example of such a system, and is illustrated in fig. 70a. If the eye is placed so that its center of rotation coincides with the center of the exit pupil of the system (the proper position of the eye when observing through a telescope), the image seen by the eye will be inverted, since it may be considered to be an infinitely distant virtual image of the inverted image produced by the objective.

In order for the telescope to be conveniently used for the observation of terrestrial objects (an inverted image makes no difference in astronomical observation), the telescope must be fitted with an *erecting system,* to invert the objective image so that it is seen in an erect position. The only essential requirement of an erecting system is, then, that it invert in two planes.

The case of the Galilean telescope, (fig. 70b) should be mentioned here. It is a simple telescope, but its eye lens is a negative lens, hence it gives an erect view of the object without an erecting system. It is the common optical system of opera and field glasses, although seldom used elsewhere, since its field of view is very small.

122. Lens Erecting System

Since a real image formed by an optical system composed of lenses is inverted in two planes, such a system is suitable

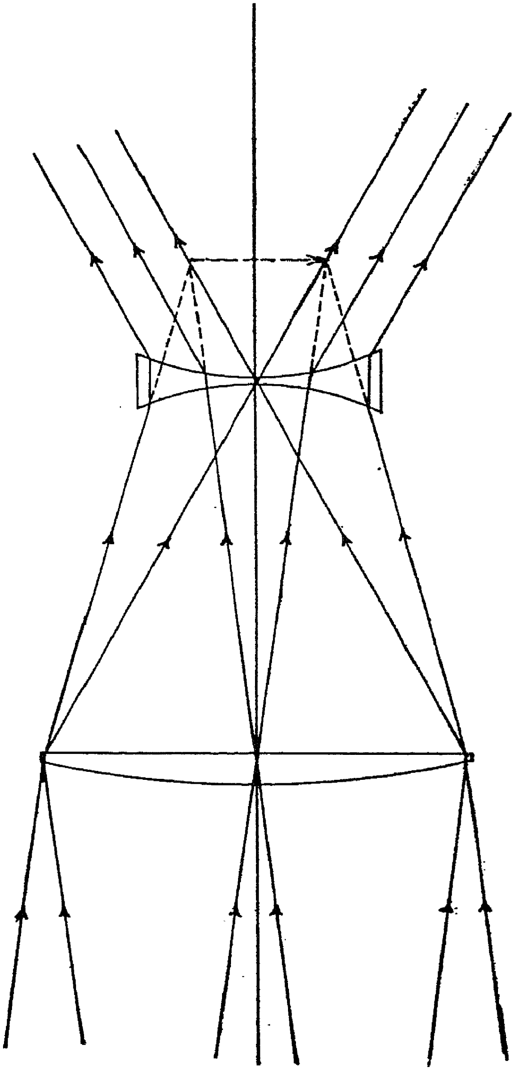


Fig. 70
The simple telescope

for use as an erecting system. It would seem that a single lens would be the simplest and most satisfactory solution, but a moment's consideration will show that this is not true.

With rare exceptions, it is desirable that the over-all length of a telescope be as short as possible. Examination of equation (15) shows that the minimum separation of object and image for a lens of given focal length is four times the focal length of the lens if the image is real and inverted. This means that in order to keep the length of the telescope within reasonable bounds, the focal length of the erecting lens must be very short, which means steep curves, difficult to manufacture and productive of heavy aberrations.

If, however, a combination of two lenses is used, the required short focal length may be achieved without the use of steep curves, and for this reason most lens erecting systems are composed of two lenses, usually separated by a considerable interval (fig. 71).

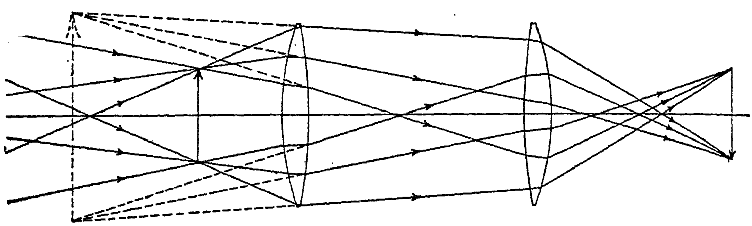


FIG. 71

Lens erecting system

A system of two thin lenses can be made aberration-free only if both components are separately achromatized, and, strangely enough, *not* free of spherical aberration independently. It is a common procedure, especially in military instruments, to make the erecting system of two identical lenses, each achromatic. The *front* erector is so placed that the image formed by the objective is located at its primary focal point, whence the light emerges in parallel bundles, to be received by the

rear erector, which forms a real image at its principal focal point. This image is, of course, inverted with respect to the objective image.

This type of system has the advantage that the separation of the two erecting lenses is not critical (since the light between them is parallel), the image is not changed in size by the erecting system, and something is gained in the cost of manufacture, since it is cheaper to build two similar lenses than two different ones. This type of erecting system, called the *symmetric* erecting system, is illustrated in fig. 72.

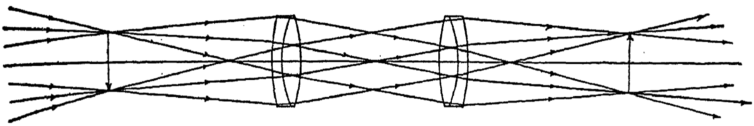


FIG. 72

Symmetrical erecting system

123. Variable Magnification

The use of a lens erecting system makes possible an instrument with variable magnification. If we examine equations (22) and (23) we see that the focal length of a combination of separated thin lenses varies with their separation, and that the magnification varies with the focal length. Therefore, the linear magnification varies with the separation. Thus by changing the separation we can change the focal length, and consequently the magnification. It should be noted that this procedure is not possible in the symmetric erecting system described above, since for all separations the linear magnification of such a system is equal to -1

When the separation between the lenses is changed, in the unsymmetrical type, the distance between object and image is also changed, and this necessitates a further adjustment in the instrument, which may be made in two different ways.

Suppose, in fig. 73, we move the rear erector closer to the

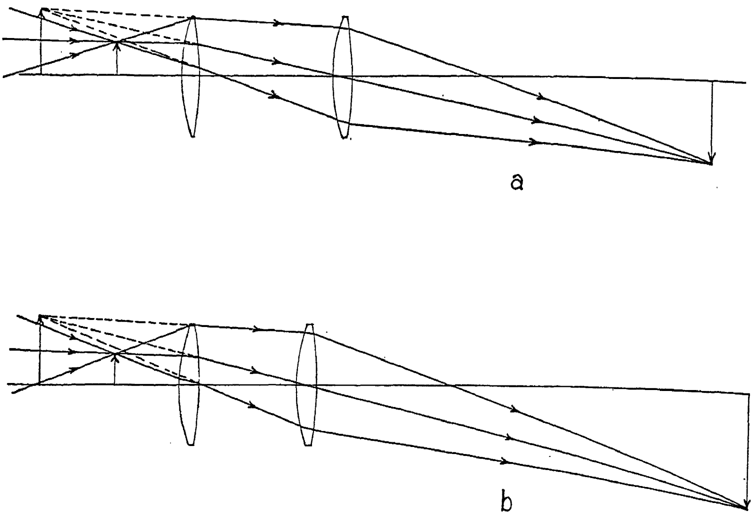


FIG. 73

Variable magnification

front erector. The rear erector is now closer to its object and thus the image will be farther away from the lens and larger (fig. 73b). But now the eyepiece will be improperly located. This condition can be corrected in either one of two ways, by moving the eyepiece itself, or by moving the front erector. In the latter case, the movement of the front erector will be less than that of the rear erector, therefore, the net separation of the two will have been decreased.

There are thus two types of variable magnification telescopes; in one, there is a movement of one of the erecting lenses and of the eyepiece (different in amount for each), and in the other, the eyepiece remains stationary, and the two erectors are moved at different velocities. The latter is more convenient and more often used. Neither method is very frequently used, however, since the simplest way of varying the magnification of a telescope consists of changing the eyepiece, as described in chapter XVII.

124. Prism Erecting Systems

When the length of the complete instrument must be made as short as possible (usually the case in military instruments), then a prism erecting system is superior to a lens erecting system, since no prism erecting system increases the length of the intrument, and many types actually reduce it. In addition, as was pointed out in chapter X, it is frequently possible to combine other desirable effects with the erection of the image through the use of prisms.

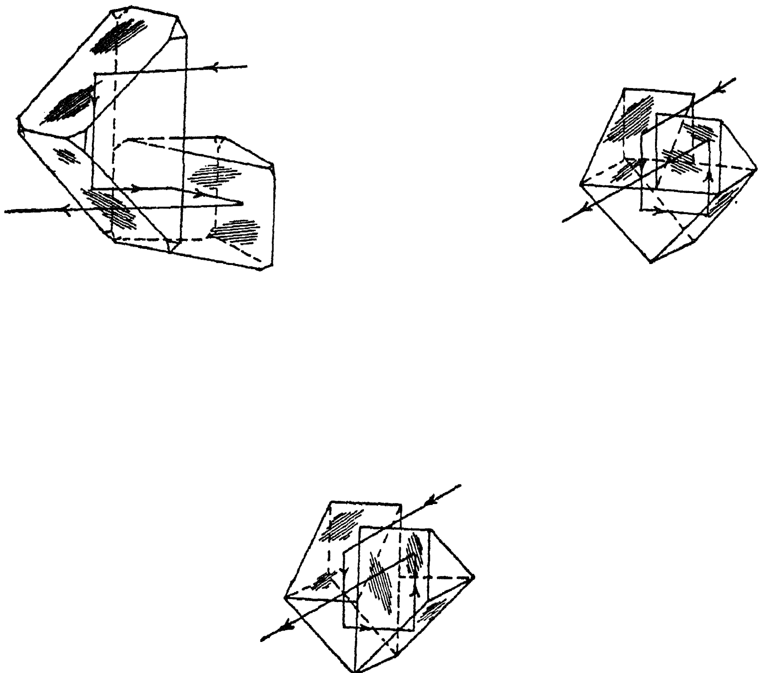
We saw in chapter X that a prism or combination of prisms which has an even number of reflecting faces will introduce two inversions, and that if the position of the reflecting faces is so arranged that an odd number of inversions occurs in each of two mutually perpendicular planes, there will be complete erection of the image.

125. Porro Prism Systems

The erecting system by Porro is one of the oldest and most widely used of prism erecting systems. It consists of two right-angle prisms so oriented that the two short sides of the triangle constitute the reflecting faces. A right-angle prism used in this way will deviate the light through 180° and, therefore, falls in the category described in (84), where an inversion in one plane is produced by two reflections and a deviation of the light through 180°.

Two right-angle prisms used in this way and mounted so that their planes of deviation are mutually perpendicular constitute the Porro erecting system. The system has four reflecting surfaces and two 180° deviations, thus producing inversion in two planes. This system is illustrated in fig. 74a.

The effect of the Porro system is to displace the optical axis without changing its direction. When used in an instrument, it decreases the length of the instrument by the total length of



b

FIG. 74

Porro prism erecting systems

the light path through the prism system plus the separation of the prisms. It is of general use in binoculars.

A modification of the Porro system is illustrated in fig. 74b and c. The modification consists of dividing one of the right-angle prisms in two and mounting these two halves side by side on the long face of the third, facing them in opposite directions. This system may be constructed in either two pieces or three, as indicated in the illustration. Theoretically it could be made in one piece, but the manufacturing difficulties would preclude this type.

126. Roof Prism Erecting Systems

It was stated in (89) that many erecting systems are of the roof prism type, and that the principle of the roof prism, two mirrors inclined at 90°, produces inversion in two planes. In a roof prism erecting system, it may be necessary to introduce reflecting faces other than the roof, in order to bring the light onto the roof at the proper angle, and if these additional faces are present, they must be even in number, and cancel each other's inversions.

Several more-or-less common types of roof prisms are illustrated in fig. 75. The Amici roof prism is the simplest and most

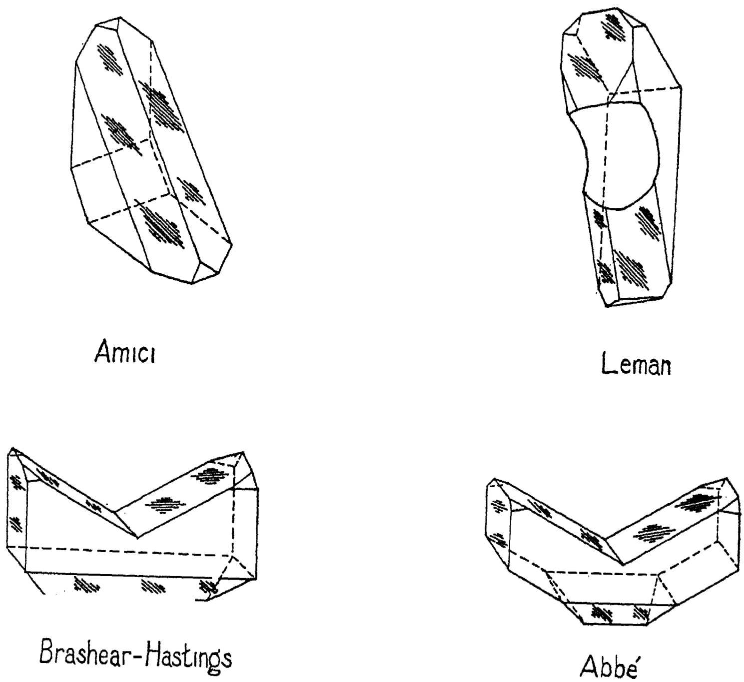


FIG. 75

Common types of roof prisms

frequently used. It gives only two reflections, but deviates the light through 90°, which is not always desirable.

The Leman prism is often used where a displacement of the optical axis is desired. It is a constant-deviation prism (88).

The Abbé and Brashear-Hastings are almost identical, and have the advantage of not displacing or deviating the optical axis.

No type can be said to be superior to others; each has its specific uses, for which it is best adapted.

127. Relative Advantages of Lens and Prism Erecting Systems

As was previously mentioned, the principal advantage of a prism erecting system lies in the fact that it shortens the instrument containing it with respect to an instrument using a lens system. Where this is not a major factor, a lens erecting system would be preferable, if only because it would be less expensive. A further disadvantage of a prism erecting system is that it is usually more difficult to collimate, and easily gets out of adjustment.

The effect of a prism (with respect to aberrations) upon an optical system is exactly the same as the effect of a plane-parallel plate. Since the light path through a prism is usually quite great, there is considerable absorption, and aberrations, especially chromatic aberration, are introduced to a small degree. The dispersion of a prism is the factor which dictates the principle that prisms should be so designed that the rays are incident and emergent perpendicularly, if possible. If the cone of rays is strongly convergent or divergent, or strikes the prism obliquely, the use of a prism will introduce serious chromatic and spherical aberration which, to make the situation more difficult, will not be symmetrical about the optical axis and consequently will not be subject to correction by succeeding *lenses*. The Dove prism (fig. 45) is so designed that the rays reach the entrance and exit faces obliquely, and if this prism

were placed in a converging or diverging cone of rays, the chromatic and spherical aberration would be intolerable. For this reason, this prism, when used, is always situated *outside* the lens system of the instrument.

Of course, when it is necessary or desirable to change the direction of or to displace the optical axis of an instrument, the use of a prism (or a mirror) for the purpose is necessary, for no combination of lenses can turn light around a corner. When this is done, if the prism mentioned produces an inversion, then a single-inverting prism elsewhere in the optical system will, with the first prism, constitute an erecting system.

CHAPTER XV

Eyepieces

128. Purpose of Eyepieces

It was pointed out in (78) that most optical instruments can be considered to be composed of two distinct optical systems, whose separation from each other determines the properties of the instrument. In the case of instruments used for visual purposes, one of these systems is the eyepiece. Such instruments (telescopes and microscopes, principally) usually perform the function of magnifying the image over the apparent size as seen with the unaided eye (angular magnification) and this magnification is determined by the relationship of the focal length of the eyepiece to that of the other optical system, the objective, as described in chapter XVII.

Eyepieces must, of course, be corrected for aberrations as far as possible, and especially for chromatic and spherical aberration and coma. A certain amount of curvature of the field must be admitted. It is often desirable to overcorrect an objective lens to compensate for an undercorrection in the eyepiece and, furthermore, since the eye itself is chromatically undercorrected, the entire optical system is often overcorrected to compensate. The design of eyepieces must not only take into consideration the residual aberrations of the remainder of the optical system with which it is to be used, but the idiosyncrasies of the human eye as well. Therefore, it is usually not satisfactory to attempt to use an eyepiece obtained at random with a telescope or microscope for which it has not been designed. The results are almost sure to be disappointing.

129. Solid Oculars

The word *ocular* is often used synonymously with eyepiece, and the reader should become accustomed to it. The simplest type of ocular is, of course, a single lens, such as was shown in the simple telescope in fig. 70a. If it is a positive lens, it does not invert the image, and consequently an erecting system must be used in the instrument if it is for terrestrial observation. An eyepiece of negative focal length, however, will give an erect image without an erecting system, as in the Galilean telescope (fig. 70b). One of the principal disadvantages of the single lens is, of course, the impossibility of correcting it for aberrations, but this is at least partially removed by making it a compound lens. Some excellent triplet solid oculars have been designed by Zeiss, Steinheil, and Hastings (fig. 76). Such oculars are very useful for high magnification.

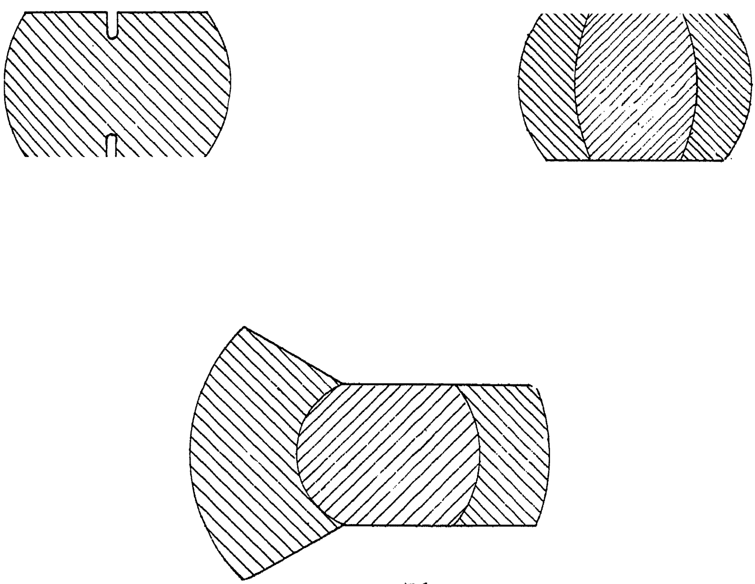


FIG. 76

Solid oculars

130. Compound Eyepieces

The inherent disadvantage of the single ocular is its small field of view. In the single lens this is only about 10°, although in the triplet systems it is sometimes possible to make it as great as 30° without too great loss of definition at the edge of the field. It is usually desirable, however, especially for low magnification, to have a field of view of from 40° to 50°, and in order to achieve this without admitting ruinous oblique abberations, we must use a *compound* eyepiece.

Compound eyepieces are of two general types, positive and negative. Since there are several different types of positive eyepieces, but only one *common* variety of the negative, we shall discuss the latter first.

131. The Huygenian Eyepiece

What is probably the earliest form of compound eyepiece is that used by Huygens, and which bears his name. It is usually composed of two thin, plano-convex lenses, mounted with the convex sides of the lenses directed toward the objective (fig. 77). The first lens, known as the *field lens,* is placed slightly inside the focal point of the objective lens, so that its object is virtual,

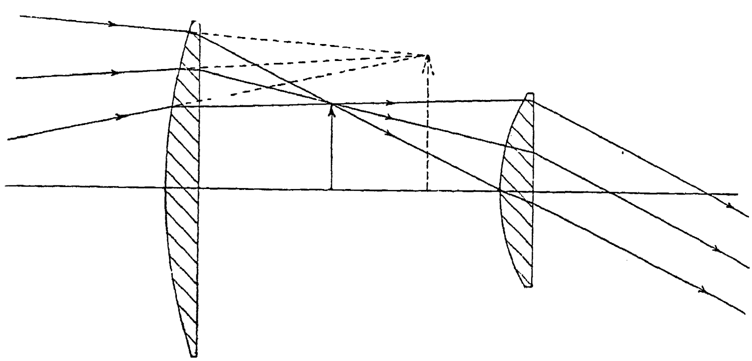


FIG. 77

The huygenian eyepiece

and it forms a real image between the two eyepiece lenses. This real image is located at the principal focus of the second, or *eye lens,* and the light emerges in parallel bundles (see below). The term negative is used because the focal point of the combination lies between the two lenses, consequently the eyepiece cannot be used as an ordinary magnifier.

The principal advantage of the Huygenian eyepiece is that it is possible to free it completely of transverse chromatic aberration. From the theory of oblique aberrations, the condition for the removal of transverse chromatic aberration from a combination of two thin lenses, according to Conrady, is:

$$d' = \frac{f'_a + f'_b \dfrac{V_b}{V_a}}{1 + \dfrac{V_b}{V_a} + \dfrac{f'_a}{s_a} - \dfrac{f'_b V_b}{s'_b V_a}}$$

where d', f', and V have their usual significance, s'_b is the distance of the objective lens from the field lens, and s_a is the distance from the eye lens at which a virtual image is to be formed (see below). This is a general form of the equation which, when we assume that both lenses are of the same kind of glass (thus $V_b = V_a$) and that the image is to be formed at infinity (light to emerge from the eye lens in parallel bundles), becomes:

$$d' = \frac{f'_a + f'_b}{2 - \dfrac{f'_b}{s'_b}} \tag{32}$$

Assuming that the distance of the objective lens is infinity yields the more commonly used expression:

$$d' = \frac{f'_a + f'_b}{} \tag{32a}$$

which, however useful it may be for preliminary computation, contains an unjustified assumption which should be noted.

Theoretically, a telescopic system should have an infinite focal length, but since those who use a telescope are frequently afflicted with ammetropia, and since younger observers find it very difficult to relax the accommodation of their eyes to the extent necessary to deal with parallel bundles of light, a properly designed eyepiece will be computed for an average virtual image distance s_a (generally about one meter), so that even the assumption that $s_a = \infty$, resulting in equation (32) is not strictly justified.

In any case, however, the condition for freedom from transverse chromatic aberration can be satisfied. The conditions for minimizing other aberrations requires that the focal length of the field lens be a small multiple of that of the eye lens. For high magnifications, a ratio of 2 to 3 is most commonly used; for low magnifications, especially in microscopes, a ratio of 1 to 4 is frequently found.

The Huygenian eyepiece has longitudinal chromatic aberration and also axial spherical aberration which, however, are usually of negligible magnitude. It gives a very large field of good definition, up to 50° if properly designed, and is the most frequently used eyepiece on astronomical telescopes.

It has, however, one inherent disadvantage. The real image is formed between the two lenses, and this image possesses a considerable residual of aberrations, which compensate the aberrations of the single eye lens. When an instrument is used with a reticle (see chapter XVI) the reticle must be placed in contact with a real image, and in the Huygenian eyepiece this would necessitate placing it between the two lenses. In this position it would be magnified only by the eye lens, and thus be subject to considerable aberration with the resultant unsatisfactory image for measuring purposes. In addition to this, the mechanical construction necessary for placing a reticle inside the eyepiece would involve considerable difficulty, especially

if the reticle were a movable one. Furthermore, focusing of the eyepiece to adjust for individual peculiarities of vision would cause the real image to shift in position, thus introducing parallax (367). Consequently, the Huygenian eyepiece is generally used only when the instrument does not have a reticle.

Certain modifications of the Huygenian eyepiece are available, notably the Airy and Mitenzwey forms, which offer a somewhat notable improvement in performance. They differ from the normal Huygens principally in the shape and separation of the lenses.

132. Positive Eyepieces

In positive eyepieces, a real image is formed by the objective (or erecting system) *outside* the field lens, and in this position it is readily available to a reticle, which in turn is magnified by the compound eyepiece as a whole and can thus be made aberration-free to the same extent as the final image. The positive eyepiece derives its name from this position of the principal focus. The field lens, of course, forms a virtual image of the real objective image, and this virtual image is located at the principal focus of the eye lens, consequently the light emerges in parallel bundles (fig. 78).

133. The Ramsden Eyepiece

The archtype of positive eyepiece is the Ramsden, (fig. 78) in which two plano-convex lenses of equal focal length are placed with their convex sides facing each other.

The usual separation permitted in the Ramsden type is about ⅔ to ¾ the focal length of the eye lens. The greater the separation, the nearer the condition for freedom from transverse chromatic aberration (equation 32a) can be satisfied, but in order to make the object-plane available to a reticle, the separation can hardly be more than ¾ f'_1, and even less than this for young and for myopic observers.

Although the Ramsden eyepiece is inferior to the Huygenian

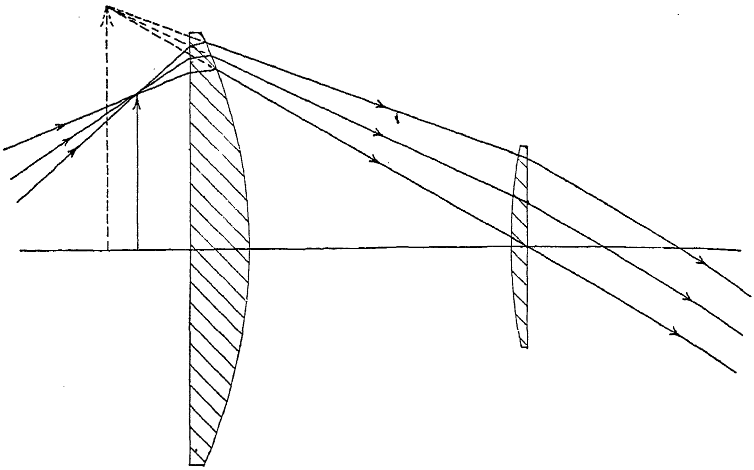


FIG. 78

The Ramsden eyepiece

with respect to transverse chromatic aberration, it is superior with respect to spherical aberration and distortion. Its field of view is slightly, but not noticeably, less and it has the additional advantage of giving a considerably greater *eye relief*, distance from eye lens to exit pupil, often a decided advantage. In the Ramsden type this distance is about 18–22 mm.; in the Huygenian type, 5–15 mm.

134. Other Types of Positive Eyepieces

A modified form of the Ramsden eyepiece is the Kellner, or as it is frequently called, the achromatized Ramsden (fig. 79a). It achieves correction of transverse chromatic aberration to a very considerable degree by making use of a compound eye lens. The equality of focal length of eye and field lenses is not maintained, the focal length of the field lens usually being about 7/4 that of the combination, and that of the eye lens about 4/3, with a separation equal to about ¾ the focal length of the combination. The principal disadvantage of this

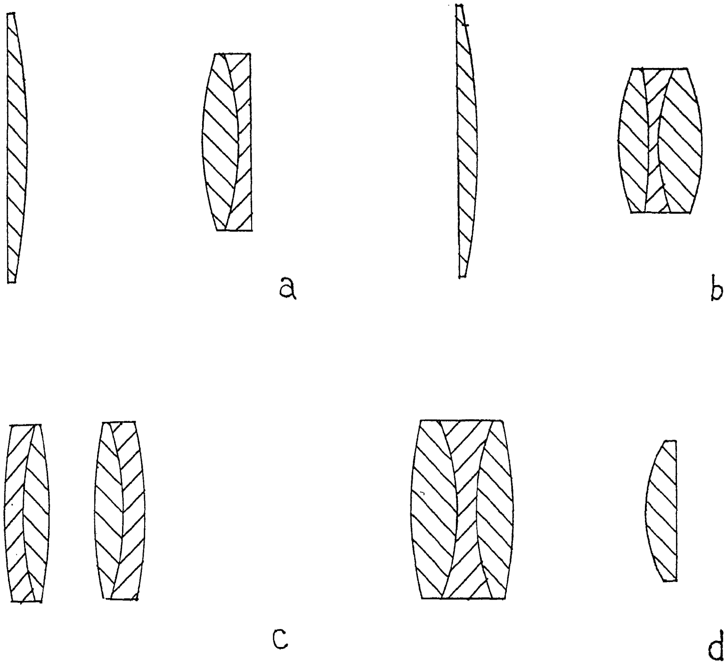


FIG. 79

Types of positive eyepieces

a. Kellner. b. French. c. Symmetric. d. Orthoscopic.

type is that the image-plane usually falls almost exactly on the anterior surface of the field lens, and thus any dust particles, scratches, or bubbles in or on the field lens become painfully visible in the field of view. Its correction for transverse chromatic aberration is not as complete as that of the Huygens; in fact, the sole reason that the eyepiece is possible at all lies in the use of a combination of dense barium crown glass and light flint glass in the eye lens doublet.

A better correction for chromatic aberration is attained in the modified form of the Ramsden known as the French eyepiece, so-called because it was indicated in instrument draw-

ings sent to the United States by the French government during the World War. It makes use of a triplet eye lens instead of the doublet of the Kellner. It is not often used except in military instruments (fig. 79b).

When long eye-relief is required, as is often the case in low-power telescopes, the symmetric, or so-called achromatic eyepiece, is used. This consists of two achromatic doublets identical with one another and almost in contact. This combination is sometimes used with a long-focus plano-convex field lens in front of the achromatic field lens to decrease the distortion (fig. 79c).

Commonly used in high-power instruments is the orthoscopic eyepiece, in which the field lens is a triplet, and the eye lens either a plano-convex or a meniscus converging lens. This eyepiece is almost completely corrected for distortion, and gives a large and quite flat field of view.

Occasionally, eyepieces will be found composed of three separated components. These are of positive type, the third lens being introduced for purposes of aberration correction.

Finally, we have the combination eyepiece-erecting system known as the terrestrial eyepiece, which is frequently furnished with telescopes, together with an assortment of ordinary (celestial) eyepieces (fig. 80).

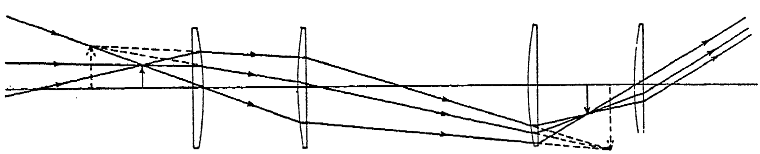


FIG. 80

Terrestrial eyepiece

In its customary form, it is actually a combination of a Ramsden eyepiece with a Huygenian eyepiece. The Ramsden combination is reversed, the eye lens receiving light from the objective, which forms its real image in the principal focus

of the complete combination. This light is picked up by the Huygenian combination, at the eye end of the ocular, which functions in the usual way. This eyepiece is essentially a compound microscope. Its disadvantage is its considerable length, which is usually about 10 times the equivalent focal length.

CHAPTER XVI

RETICLES

135. Definition and Purpose of Reticles

When an instrument is used for measuring purposes, it is necessary that it has a reticle. A reticle is any reference marking, such as a fine line or a scale marking superimposed on the field of view. The purpose of a reticle is twofold. A reticle indicates, in the field of view, the location of the optical axis of the instrument; further, in some reticles, scales are provided which enable the observer to measure small angles without resort to mechanical operation of the instrument. Occasionally scales are provided (as with range finders) which indicate quantities which the instrument is designed to measure. But in these cases, it cannot be said that the reticle serves to measure these quantities directly.

136. Position of Reticles

The reticle is placed exactly in the focal plane of some real image in the instrument, which may be the image formed by the objective or, more frequently, that formed by the erecting system. Thus placed, it is magnified with the image, and presented to the eye simultaneously with the image of the field of view.

If the instrument is not in correct adjustment, it may be that the image does not fall exactly upon the reticle, in which case, if the eye is moved slightly from side to side, the reticle markings can be seen to shift back and forth across the field of view. This condition is known as *parallax*. (See adjustments in 367.)

137. Construction of Reticles

When it is not necessary that any scales should be a part of the reticle, and fine lines across the field of view are sufficient for the purposes desired, then a reticle may be made of fine thread, wire, or spider web. Spider web is the most commonly used material in the case of theodolites and scientific instruments, which are not subject to rough handling. Surveying instruments for use in tropical countries are frequently furnished with reticles made of platinum wire, because of the effect of heat and humidity upon the spider web. Fine steel wire is sometimes used if the reticle lines do not have to be too delicate.

If the reticle is to be sturdy, however, and if scale markings are necessary, the scale must be marked upon a plane-parallel piece of glass. The usual method is to etch the markings with hydrofluoric acid vapor after the pattern has been engraved in wax. Occasionally the markings are printed or lithographed in inexpensive instruments. The glass must, of course, be made accurately plane-parallel and flat.

138. Types of Reticles

Fig. 81 shows several types of reticles in common use. (a) is a plain cross-hair type, similar to that used in ordinary surveying instruments, and frequently in finder telescopes used with astronomical instruments to bring an object into the field of view of the main instrument. (b) shows the reticle most commonly used on astronomical transit instruments. The double parallel lines are adjusted to lie on a declination circle, so that the star transiting the meridian may be followed between the wires and the instrument kept in proper adjustment. (c) shows a reticle frequently used in surveying instruments. The distance between the two extreme horizontal lines corresponds to a specified angle in the field of view, and by observing the number of scale readings subtended by this angle on a sur-

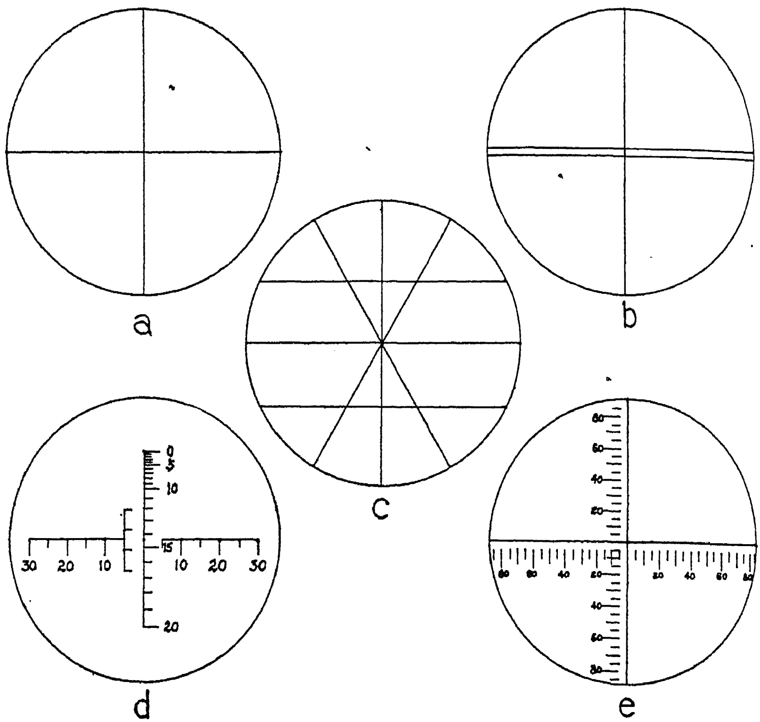


FIG. 81

Types of reticles

veyor's rod, the distance of the rod from the instrument can be easily calculated. (d) is the reticle of a military binocular. The graduations on the horizontal scale each correspond to an angle of 10 mils (1 mil = 1/6400th of a complete circle) and the vertical scale is an inverted copy of the leaf sight of a certain military rifle, for the purpose of locating indirect aiming points when the actual target is not visible to the rifleman's unaided eye. (e) is the reticle of the aiming circle, a military transit instrument, used to measure angles in both horizontal and vertical planes. Each graduation corresponds to five mils.

139. Scale Markings on Reticles

The scale markings on a reticle such as (d) and (e) of fig. 81 must be accurately placed and computed for the particular instrument with which the reticle is to be used.

The linear subtension of the angle θ in the field of view of an optical system is equal to:

$$f' \tan \theta$$

where f' is the focal length of the objective lens, as shown in fig. 82. If there are lenses interposed between the objective and

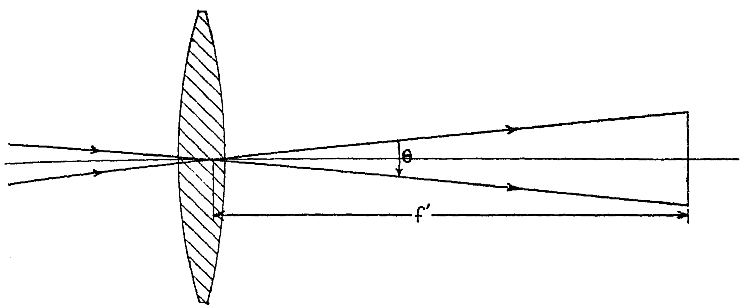


FIG. 82

Linear subtension in the field of view

the plane of the reticle, this equation will be untrue, unless the lenses are such as to produce an image at the reticle with a linear magnification of unity. It is immediately evident that this condition is not maintained unless the erecting system is of the type described in (122), where the focal lengths of the two erecting lenses are equal and the objective image is placed at the principal focus of one of them, the symmetric erecting system. The condition is, of course, satisfied in instruments using prism erecting systems. It is definitely not satisfied in instruments with variable magnifying power. The equation is not voided by any lenses which may occur in the system *behind* the reticle, since such lenses will have the same magnifying

effect on the reticle as they have on the image. Of course, an appropriate equation can be worked out for any system with any number of lenses preceding the reticle, provided that these lenses are stationary.

140. Illumination of Reticles

When an instrument is to be used for night or dusk observation, the illumination of the image is usually not sufficient to make the markings of the reticle visible, and in these cases it is necessary to illuminate the reticle with an outside source. This is generally a very small electric lamp so mounted as to shine through a small hole on the side of the instrument beside the reticle. This type of illumination works best with glass reticles, although reasonably well with the wire and hair types.

PART II

DESCRIPTION, OPERATION AND THEORY OF OPTICAL INSTRUMENTS

CHAPTER XVII

THE TELESCOPE

141. Definition and Purpose

An optical system whose focal length is infinity constitutes an afocal or *telescopic* system (78). A large majority of optical instruments are either telescopes or contain telescopes as part of their optical systems.

A telescope may always be thought of as a combination of two optical systems so spaced that the secondary principal focal point of one system coincides with the primary principal focal point of the other. In this way, an image of an infinitely distant object is formed by the first system at the principal focus of the second, and thus the light emerges from the second system in parallel bundles, and an image is formed at infinity.

The chief purpose of a telescopic system is the observation of distant objects with the eye.

142. Principal Parts of a Telescope

The two optical systems referred to above are the *objective* and *eyepiece* of the telescope, respectively. The instrument may also contain other optical parts, such as an erecting system, reticle, prisms, etc., but these are secondary to the main telescopic system.

The objectives of telescopes are almost without exception carefully corrected achromatic lenses. Sometimes, in the case of astronomical telescopes, they are of considerable size. Compound eyepieces are generally used, except for the higher magnifications, and will usually be of the Huygenian type (131) unless a reticle is to be used. Lens erecting systems of the

type described in (122) are most frequently used, often combined with the eyepiece (134).

143. The Keplerian Telescope

The telescope, when it consists only of an objective and a single eye lens, is called a *simple telescope,* as opposed to a *compound telescope,* which contains an erecting system and/or a compound eyepiece. All telescopes used for terrestrial observation have erecting systems, and practically all telescopes use compound eyepieces.

The simple telescope exhibited in fig. 83 is a Keplerian telescope, in which both the objective and the eyepiece are converging lenses. It is the basic type of nearly all refracting telescopes. The final image, of course, is inverted to an eye placed behind the instrument, and in order for terrestrial objects

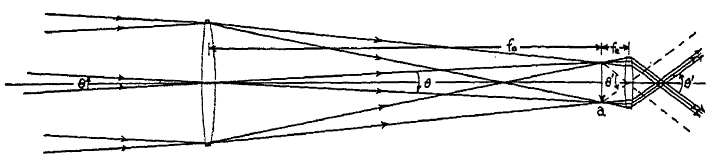


FIG. 83

The simple telescope; Kellerian

to be conveniently viewed, an erecting system must be added to the instrument. For astronomical purposes, inversion of the image is no disadvantage, and erecting systems are omitted, thus saving not only in cost and size of instrument, but in the absorption of light in the optical system.

144. The Galilean Telescope

Another type of simple telescope is possible, the Galilean type (fig. 84), in which the convergent eye lens of the Keplerian type is replaced with a negative lens. This telescope gives an erect image without the necessity for an erecting system.

The image formed by the objective constitutes a *virtual object*

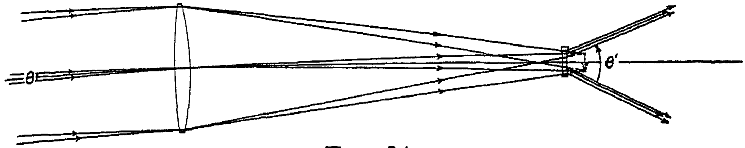


FIG. 84

The simple telescope; Galilean

for the eye lens. Since the eye lens itself acts as field stop (91), the field of view of this instrument is always small, therefore it is not generally used. It is the optical system of opera glasses, and occasionally night binoculars are made in this way, because of the saving in light transmission occasioned by the absence of an erecting system.

145. Magnification of the Telescope

With a few exceptions, there is nothing to be gained in observing a distant object through an instrument rather than with the naked eye unless the instrument magnifies the image. Thus, almost all telescopes have a considerable magnifying power, varying from 4 to 6 for field glasses and hand telescopes (occasionally less in certain military instruments) to 1000 or more in the case of large astronomical telescopes.

Since object and image of a telescope in normal use are both at infinity, we must resort to the concept of *angular magnification* (86) to develop a measure of the magnifying power of the instrument. Equation (25) gives:

$$\text{Angular Magnification} = \text{MA} = \tan \theta'/\tan \theta$$

Adopting any point on the image formed by the objective (such as "a" in fig. 83) we see at once that:

$$\frac{\tan \theta'}{\tan \theta} = \frac{f_o}{f_e} \qquad (33)$$

and, therefore, the magnifying power of a telescope is the ratio

of the focal lengths of objective and eyepiece. If there is magnification in the erecting system, it must be taken into account in the determination of the magnifying power of the instrument, which will be the product of the separate magnifying powers (angular) of the telescope and the erecting system.

Thus, the most effective means of changing the magnifying power of a telescope is by changing the focal length of either the objective or the eyepiece. The most convenient is, of course, the eyepiece, and for this reason telescopes, especially astronomical telescopes, are usually furnished with several interchangeable eyepieces of different focal lengths. These eyepieces are sometimes mounted in a turret so that any desired one may be brought into use by rotating the turret. In other cases, the eyepiece is fitted into a smooth sleeve and may be easily removed and replaced by another.

Methods of varying the magnifying power by movement of the erecting system and eyepiece are described in (123), and are used where the situation calls for changing the magnifying power very quickly or for a continuous variation of magnification over a specified range.

A crude method of estimating the magnification of a telescope is to examine any suitable surface showing a pattern of equally spaced marks, such as a brick wall, using one eye directly and one eye behind the telescope. With some practice, two images can be seen, superimposed, and the number of bricks of the direct image contained in one brick of the magnified image gives the magnifying power. The same test can be made with considerable accuracy by means of another telescope whose objective lens is sufficiently large in diameter to permit light to enter it around the sides of the instrument being tested.

146. Field of View

The field of view of an optical system was discussed at some length in chapter XI, where it was shown that it depends upon the diaphragms of the system. In a telescope, the objective it-

self almost always acts as aperture stop and a field stop is usually provided at the real image formed by the objective. Antiglare diaphragms are sometimes found in telescopes, especially in those which have an objective of long focal length.

147. Apparent Field of View

Reference is frequently made to the *apparent field of view* of an instrument. This is the field of view of the eyepiece, or the angular diameter of the field stop as seen through the eyepiece from the exit pupil.

Since the apparent field of view is the size of the true field of view as seen by the eye, the ratio of the apparent field of view to the true field of view must give the magnifying power. That is,

$$\text{Angular Magnification} = \text{MA} = \frac{\text{Apparent Field}}{\text{True Field}} \qquad (33a)$$

This also follows from the fact that, in equation (33), θ is the semidiameter of the true field of view, and θ is the semidiameter of the apparent field of view.

The structure of the human eye sets a practicable limit to the size of the apparent field, since it is advisable to restrict it to the region possible for the eye to clearly focus upon without movement of the observer's head. This is about 40°–50°; and because of the relation between the true and apparent fields of view and the magnifying power, the true field of view of a telescope is limited by its magnifying power, being, for practical purposes, 40°/MA.

Further, it is impracticable to construct eyepieces of very short focal length (to produce high magnification) with fields of view as great as 40°, because of aberrations, and, therefore, for high magnifications, the field of view is restricted still further. In the case of a large astronomical telescope working at a magnification of 500X, the true field of view is about 2′ of arc (1/15 the apparent diameter of the moon).

148. Relation of Magnification to Entrance and Exit Pupils

It can be seen from fig. 85 that the diameters of the entrance and exit pupils are proportional to the focal lengths of objective and eyepiece, respectively, so:

$$\text{Angular Magnification} = \text{MA} = \frac{\text{Entrance Pupil}}{\text{Exit Pupil}} \qquad (33b)$$

Thus the magnifying power of a telescope may be said to be the degree by which the telescope concentrates the incident beam of light. This relationship also affects the practical limits of magnification and aperture of a telescope. It would be futile to provide an exit pupil larger than can be conveniently used by the observer, since the result would be merely to waste light

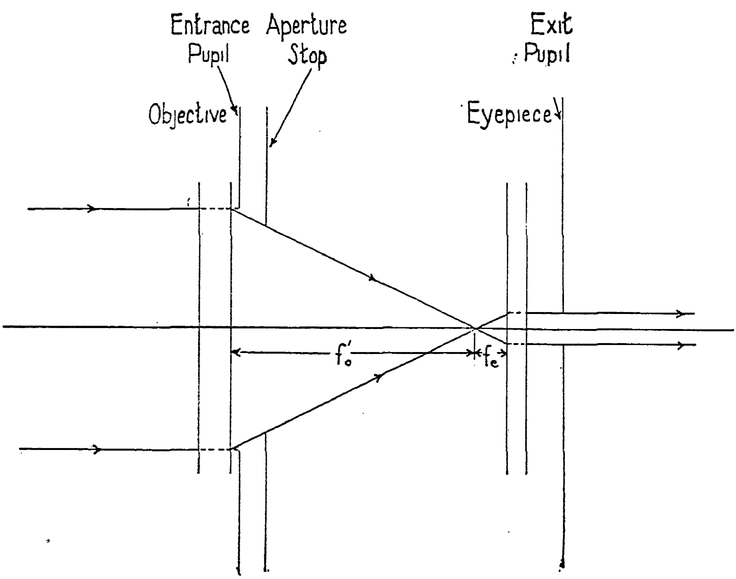


FIG. 85

Relation of entrance and exit pupils, focal lengths and magnification

and to reduce the brilliance of the image. So, there is a minimum practicable magnification and a maximum practicable aperture.

149. Illumination

The amount of light used in forming the image is dependent upon the aperture (entrance pupil) of the instrument. So, for a given magnification the image is more and more brilliantly illuminated as the aperture increases, *up to the point where the exit pupil* (which has been growing with the entrance pupil) *is equal in diameter to the pupil of the observer's eye,* after which no advantage is gained, because the additional light cannot enter the eye. Now, if the exit pupil is of this optimum size, then the ratio of the amount of light entering the eye from the image to the amount of light which would enter the eye on direct vision (neglecting losses in transmission through the optical system) is exactly equal to the magnifying power. Consequently the object in view appears larger, and its image upon the retina of the eye is larger, in the same proportion that it appears brighter.

The conclusion to be drawn is that a telescope can never make an object appear brighter than it is to the unaided eye, indeed, it is never quite as bright, due to absorption loss. This might seem incredible to anyone who has observed with night glasses, but it is perfectly true. It is a well-known fact in astronomy that an *extended object,* such as a faint nebula, if too faint to be visible to the unaided eye, can never be brought to view by any optical aid.

This restriction does not apply to *point* objects, such as stars, however. If an object is truly a point, magnification cannot make it appear larger, thus the concentration of light in the image may be increased by increasing aperture. Therefore, large-aperture astronomical telescopes can bring out *stars* too faint to be seen with the unaided eye. The necessary high magnification merely serves to make the stars farther apart,

but does not increase their individual size, so long as the magnification is below the resolving power of the instrument (411).

Cameras, of course, are not subject to this restriction, since their action is cumulative. All that is necessary to take a picture of a faint object is to give a sufficiently long exposure.

150. Terrestrial Refracting Telescopes

Telescopes containing erecting systems may be classed under the general term *terrestrial telescopes.* The most common form is the familiar *spyglass,* from whose collapsible tube the verb telescope is derived. This instrument contains an objective and a terrestrial eyepiece (134).

When interchangeable eyepieces are used, however, the erecting system will be separate from the eyepiece and mounted in the body of the instrument. This erecting system may be composed of either lenses or prisms, as outlined in chapter XIV.

Terrestrial telescopes are never very large, since their purposes usually demand that they be portable, and there is a definite limit to the magnification of a portable instrument. No instrument with a magnification greater than 8X can be held steadily enough in the hands to permit really clear vision. With a firm mounting, higher powers are, of course, possible, but, because the field of view becomes almost incredibly small at high powers, a really powerful instrument requires a permanent and elaborate mounting, such as is found on the large astronomical telescopes. Terrestrial telescopes, therefore, rarely have a magnification of greater than 50X, even when mounted on sturdy tripods.

151. Telescope Mountings

High-power terrestrial telescopes are usually mounted on tripods, making them more or less portable. Customarily, the tripod has folding or collapsible legs. The *mounting,* which term is usually reserved for the mechanism existing between the instrument proper and the tripod support, will generally

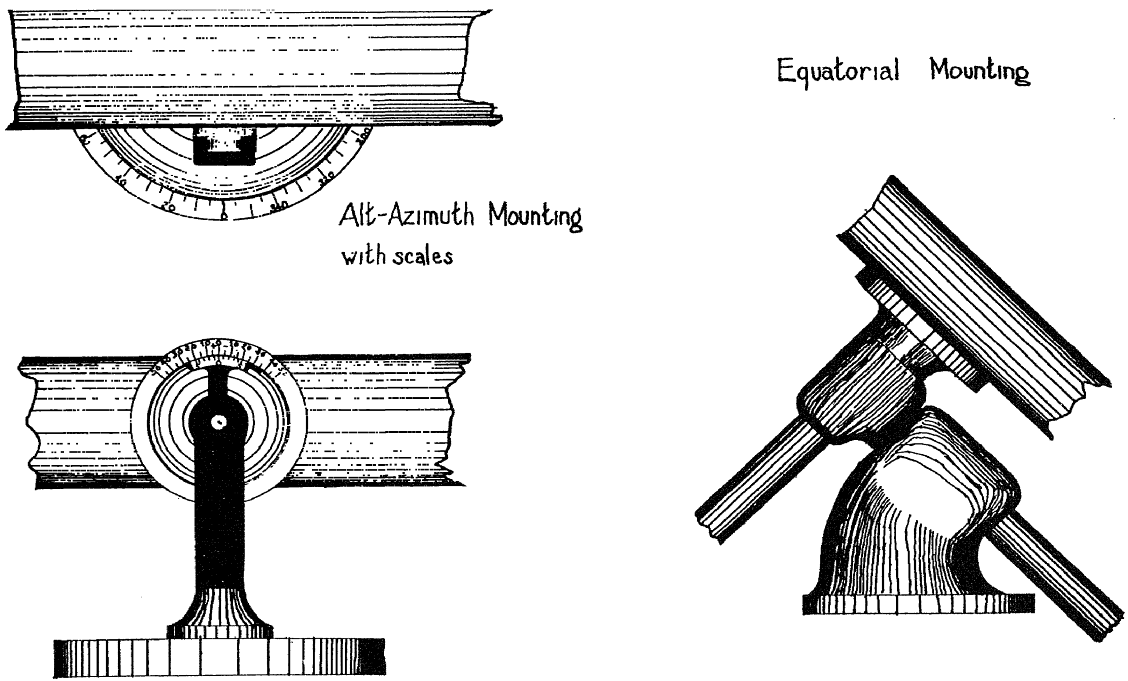


FIG. 86

Types of telescope mountings

be designed to provide rotation in two planes, in *azimuth* or *bearing* (horizontal movement) and in *elevation* or *altitude* (vertical movement). It may be provided with a leveling device, so that the rotation may be made truly horizontal and vertical. This is especially necessary if there are azimuth and elevation scales on the mounting (fig. 86).

Astronomical telescopes are mounted upon *equatorial* mountings, maintaining the principle of rotation around two perpendicular axes, but with the azimuth axis tipped so as to be parallel to the axis of rotation of the earth. In this way, the motion of a star across the sky can be followed by rotation of the instrument upon this axis, the *polar* axis, alone. This position of the axes also coincides with the co-ordinates in which star positions are defined, *right ascension* (or *hour angle*) and *declination.* Graduated circles are, of course, provided for setting the instrument in the proper direction. Such a mounting must be very carefully oriented for a particular latitude and so cannot be conveniently made portable, although the equatorial principle can be and frequently is employed on tripods for small astronomical telescopes, the polar axis being aligned approximately on the pole star when the instrument is being used.

152. Mounting of Lenses

Lenses are usually mounted in cells in either one of two ways, with a *retaining ring,* or *burnished.* The cell is a short cylinder, threaded on the outside to fit the body of the instrument, and, if a retaining ring is used, threaded on the inside for this ring (fig. 87). Burnishing refers to an operation by which the rim of the cell is rolled over on a lathe to hold the lens securely and permanently in place (fig. 87).

The cell is bored to a sliding fit for the lens, with a clearance of 0.002″ to 0.005″ all around the lens. The lens should slide easily in and out of the cell, but should not be free to shift about laterally. The retaining ring is screwed down so as to hold

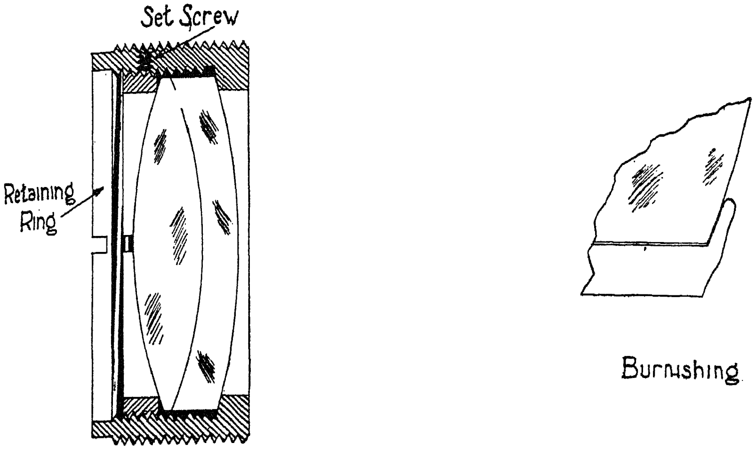


FIG. 87

Mountings of lenses

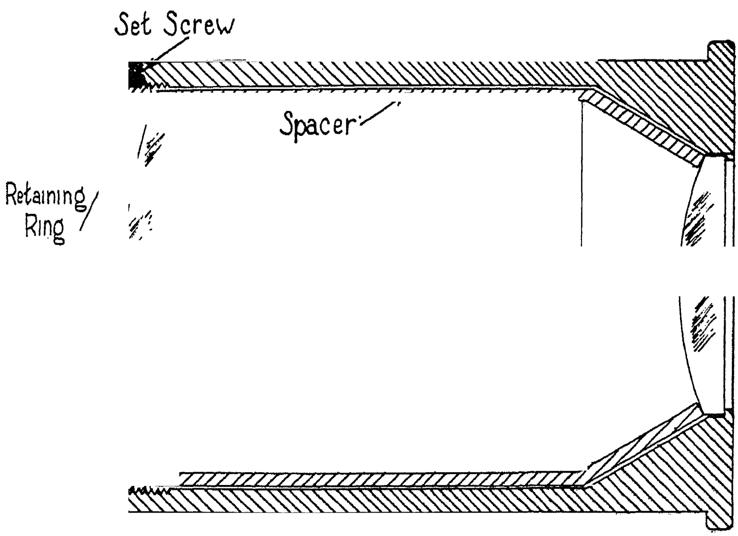


FIG. 88

Eyepiece mounting with spacer

the lens firmly but not tightly. If the ring is too tight, it may distort the lens curvature and introduce aberrations. It is usually held in place by a setscrew through the wall of the cell.

In some cases, two or more lenses are placed in a single cell, and the lenses held in proper relation to one another by spacers, metal cylinders which fit smoothly into the cell. Eyepieces are usually mounted in this way (fig. 88).

In small telescopes, the objective cell is usually threaded into the main tube of the instrument, but in larger instruments provision is generally made for "rocking" the objective to collimate the telescope. In such cases, the tube and the objective cell carry flanges upon which are placed the adjusting screws, almost always of the push-pull type (figs. 89, 90).

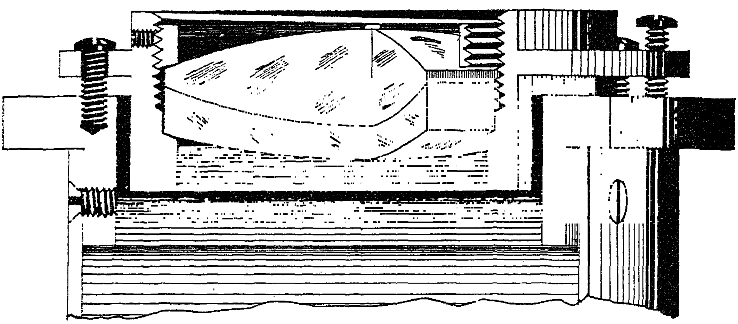


FIG. 89

Adjustable objective cell

153. Focusing Eyepieces

It was pointed out in (131) that although a telescopic system in *normal* adjustment has its final image at infinity, it is frequently the case that an observer, due to ammetropia or individual perversity, can see most clearly if an image at a finite distance is provided.

It is evident that a change in the position of the eyepiece will change the position of the final image produced by the instrument. If the eyepiece is moved toward the objective, the

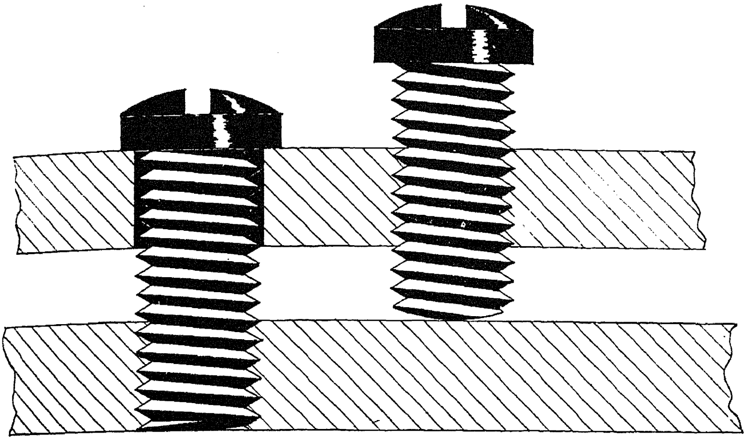


FIG. 90

Push-pull screws

image will be virtual and at a finite distance in front of the eyepiece, and the light leaving the eyepiece will be divergent; if the eyepiece is moved away from the objective, a real image will be formed at a finite distance behind the eyepiece, and the light will be convergent. We have found (99) that myopia requires divergent light and hyperopia requires convergent light, thus we see that a slight movement of the eyepiece of a telescope toward or away from the objective will correct the emerging light for any myopia or hyperopia of the observer, making it unnecessary for him to wear spectacles when using the instrument. Indeed, it is advisable not to wear glasses when using an optical instrument, since the eye position is usually so close to the eyepiece that spectacles would prevent the eye from coming into its proper position. Furthermore, extraneous light reflected from the back surface of the spectacles will affect the apparent brightness of the field of view. Of course, if the observer is using an instrument in which the eyepiece is not adjustable, or if he has eye defects other than ammetropia, such

as astigmatism, it will be necessary for him to wear spectacles when observing.

It was mentioned in (131) that young observers prefer to work with a fairly close virtual image, which requires that the eyepiece be placed closer to the objective than normal adjustment would require. For these reasons, and also because interchangeable eyepieces make it necessary that the position of the eyepiece be adjustable, the eyepiece cell is usually carried in an adjustable sleeve, called a *drawtube*. This sleeve may be mounted into the telescope tube on a thread or on a rack and pinion gear (fig. 91). In the case of a threaded mounting, it

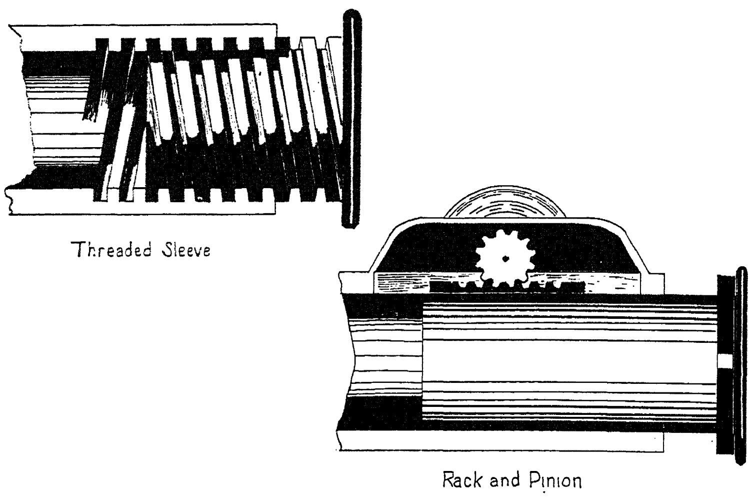


FIG. 91

Adjustable eyepiece mountings

is generally a multiple thread, to provide a large lead. Such eyepieces are called *focusing eyepieces*.

Sometimes telescopes are focused by moving the objective on a rack and pinion, leaving the eyepiece stationary, and occasionally the objective is made of the telephoto lens type (181), with a negative lens behind and at some distance from

the positive component, and focusing is done by moving this negative lens on a rack and pinion.

Focusing devices of this type cause a variation in the position of the real image for different focusing positions, thus, if a reticle is used in the instrument, parallax (367) cannot be removed except for a specific location of the final image (that is, for a particular observer). Such arrangements do, however, permit the focusing of objects at varying distances without the introduction of parallax, and for this reason are frequently used in surveying instruments.

154. Diopter Scales

A scale is frequently found on focusing eyepieces to indicate the amount of displacement (fig. 92). These scales are known

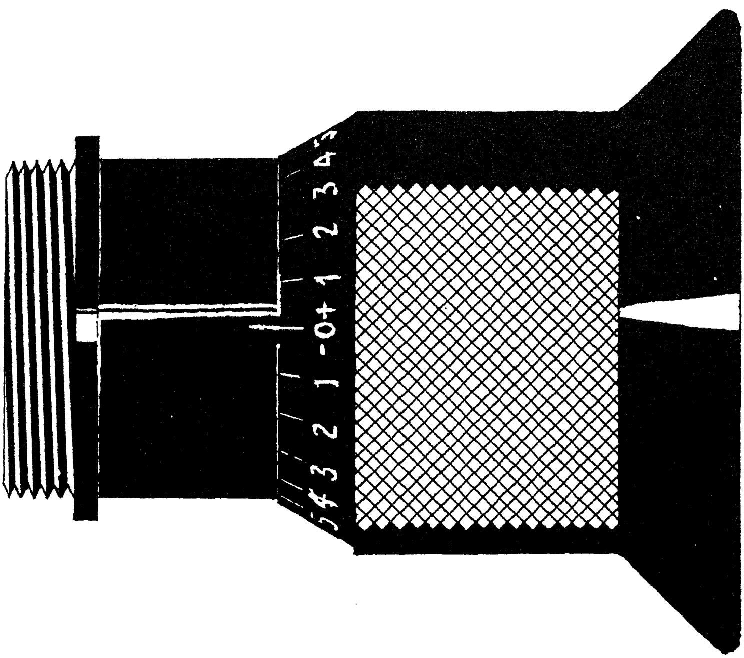


FIG. 92

Eyepiece with diopter scale

as *diopter scales,* and their setting indicates the refracting power (69) of the instrument in diopters. By means of such a scale, an observer can set off the proper correction for his eye with a minimum of effort.

155. Astronomical Refracting Telescopes

The great astronomical telescopes are, of course, the outstanding examples of telescope design. The astronomical telescope has no erecting system, because it makes no difference whether a field of stars is seen inverted or erect.

As a problem in optical design, an astronomical telescope presents no particular difficulties. The correction of its objective must be as perfect as possible * but, due to the customary long focal length (15 times the diameter) and the correspondingly small field of view, little trouble is experienced with the oblique aberrations, and it is necessary for the designer to worry only about spherical and chromatic aberration which, as we saw in chapter XIII, are easily conquered in most cases. Secondary spherical aberration is the most disturbing factor, and it is this, more than any other one thing, which puts a limit on the possible size of refracting telescopes. The largest which has so far been constructed is the 40″ diameter Yerkes Observatory telescope. For larger sizes, the reflecting telescope is superior (see below) and it is doubtful if any more very large refractors, even as large as those now in use, will ever be built.

From the construction point of view, a large objective lens is a very difficult problem. The casting of a sufficiently large block of optical glass is a problem in itself, and the grinding and

* Astronomical objectives must be much more thoroughly corrected for aberrations than those of instruments used for terrestrial purposes; thus telescopes and binoculars which are excellent for terrestrial observation may often be found to be woefully inadequate for celestial use. Prospective purchasers are warned to test on stars any instruments which they intend to use for even occasional astronomical observations.

polishing of such a huge lens, to the very close tolerances necessary, is a task requiring the utmost patience and skill.

In astronomical work, the extreme faintness of most celestial objects makes it important that the greatest possible amount of light be available in the image, and this is the only reason that very large telescopes are constructed. The high magnifications theoretically possible with such huge instruments are never realized, because the lack of homogeneity and clearness of the earth's atmosphere makes it impossible. It is light-gathering power above all things that the astronomer desires, and this explains his continual demand for larger and larger objectives.

Light-gathering power is proportional to the area of the aperture, and thus to the square of the diameter of the objective (since astronomical telescopes normally possess no aperture-restricting diaphragms). Therefore, telescopes of larger diameter will reveal fainter stars, which, on the whole, lie farther away in space. Therefore, telescopes, as they grow in size, expand the astronomer's range of vision and make his already incredibly vast universe even vaster. The faintest objects which can be recorded on long-exposure photographs with the 100″ diameter Hooker reflector at the Mount Wilson Observatory are very faint extragalactic nebulae at an estimated distance of 500 million light-years, or approximately 3,000,000,000,000,000,000,000 miles. The 200″ telescope for the observatory on Mt. Palomar will double this distance.

The general reader is not likely to become acquainted with any of the many accessory instruments for astronomical telescopes, and they are, therefore, beyond the scope of this volume.

156. Reflecting Telescopes

It was explained in (44) that concave mirrors can form real images in the same manner as converging lenses; it is, therefore, possible to use a concave mirror as the objective of a telescope. A mirror possesses certain inherent advantages over

a lens, chief among which is complete freedom from chromatic aberration (because the law of reflection is not dependent upon wave-length).

Since a real image formed by a concave mirror is in front of the mirror, it cannot be observed directly without blocking off the incident light, so a second mirror (or prism) must be interposed to deflect the image to a point where it can conveniently be observed. The image may be deflected through a right angle, as in the Newtonian form of reflecting telescope (fig. 93) or back through a hole in the center of the objective mirror, as in the Cassegrainian and Gregorian forms (figs. 94, 95). After perusing part I, the reader should be sufficiently versed in optics to realize immediately that the hole in the

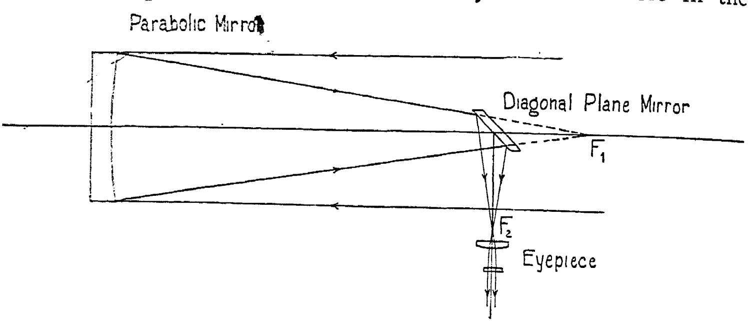


FIG. 93

Newtonian form of reflecting telescope

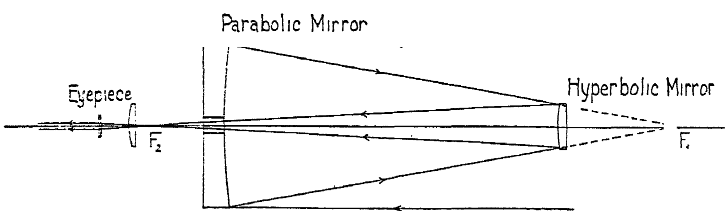


FIG. 94

Cassegrainian form of reflecting telescope

objective will merely affect the *total amount* of light present in the image, and will not introduce a blank space in the center of the field; also that the presence of a secondary mirror and its supports in the incident beam of light will not cause a silhouette in the image.

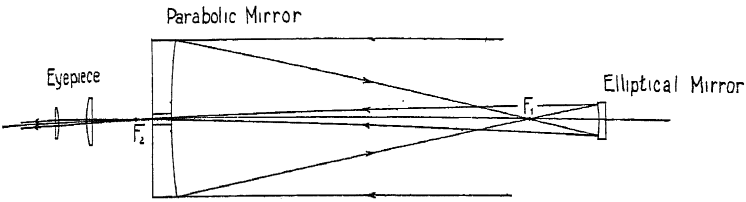


FIG. 95

Gregorian form of reflecting telescope

157. The Paraboloidal Mirror

A concave spherical mirror used as a telescope will introduce an intolerable amount of spherical aberration in the image, since a mirror will produce spherical aberration in the same manner as a lens. But in the case of a mirror it is not possible to balance the spherical curvatures of a number of associated surfaces. There is only one surface in this case, and any correction for aberrations must be made by changing the curvature of this one surface, that is, by departing from a spherical curve.

It can be shown that the required curve on a reflecting surface to form a point image of an object-point located at infinity on the optical axis is a parabola (appendix I, fig. 96). Indeed, this is a part of the definition of a parabola. For this reason, the objective mirrors of most reflecting telescopes are parabolas, or, more accurately, paraboloids of revolution, the surfaces produced when parabolas are rotated about their axes. An objective mirror is a section of such a surface taken around the vertex.

The departure of such a surface from a sphere is extremely

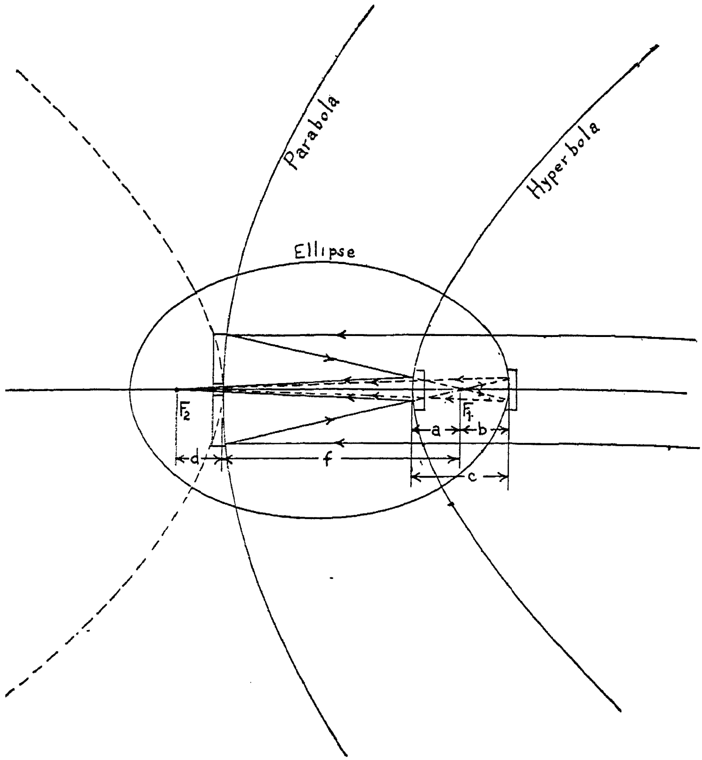


FIG. 96

Relationship of curves for Cassegrainian, Gregorian and Newtonian telescopes

slight in the region very close to the vertex which represents any conceivable objective mirror, being equal to:

$$\frac{y^4}{8r^3} \qquad \text{(Appendix I)}$$

which, even for the 200″ mirror is only 0.21″ at the extreme ed e. The difference is so slight that on mirrors of ordinary size, it is produced by *polishing* after a spherical surface has

been attained (330). In the above expression, r is the radius of curvature at the vertex, and y is the distance away from the vertex at which the measurement is being taken.

158. The Newtonian Reflecting Telescope

The Newtonian form of reflecting telescope (fig. 93), so-called because it was developed by Sir Isaac Newton, consists of a paraboloidal mirror mounted in the base of a tube, a flat mirror (or prism) at the top to deflect the image through 90°, and an eyepiece at the side of the tube. Eyepieces used on reflecting telescopes are usually positive eyepieces.

The secondary diagonal mirror (or prism) is mounted on a *spider* of either three or four legs, four being preferable. These legs are usually of very thin material, in order to block off as little light as possible, and are made fairly wide for rigidity.

Focusing is generally accomplished by a rack and pinion on the eyepiece or a threaded eyepiece cell, in the same fashion as in refracting telescopes.

159. The Cassegrainian and Gregorian Telescopes

To make a reflecting telescope reasonably efficient, not more than 25% of the incident light (preferably much less) should be blocked off by the secondary mirror, which means that the diameter of the secondary mirror should not be greater than half that of the primary. Now, if it were desired to reflect the light back through a hole in the center of the primary mirror by means of a flat mirror, this mirror would have to be greater than half the diameter of the primary, since, if exactly half, it would have to be placed at half the distance to the focal-point in order to intercept the entire cone of rays, and the final image-point would, therefore, be at the surface of the primary mirror. But it is necessary to bring the image somewhat farther back, that is, through the thickness of the mirror, its cell, and a short length of eyepiece tube.

It is, therefore, impracticable to use a *flat* mirror to form an image behind the primary mirror. In order to extend the image position, a curved mirror must be used. In the Cassegrainian form of reflector, a convex mirror is mounted just inside the principal focus of the primary mirror, and forms an image at a point behind the primary (fig. 94). The form of the secondary mirror surface is that of a hyperboloid of revolution, since a necessary property of the hyperbola is that an object at one focus will have a corresponding real image, free of spherical aberration, at the other focus. Thus, in the Cassegrainian telescope, the secondary mirror is a hyperboloid of revolution, one of whose foci coincides with the principal focus of the primary mirror, and whose other focus represents the position of the final image of the instrument.

It will be seen that the effective focal length of such an instrument is considerably greater than that of the primary mirror alone, but that the length of tube necessary to contain the instrument is about equal to the focal length of the primary; therefore, a Cassegrainian represents a very compact form of telescope, a very decided advantage in the case of large sizes. One of the most difficult mechanical problems in the very large refractors is the necessity of supporting a tremendous length of tube (about 50 feet in the case of the Yerkes telescope) without flexure.

In the Gregorian form of reflecting telescope, the secondary mirror is concave, and is placed outside the principal focus of the primary mirror, in the diverging cone of rays (fig. 95). Its object is real, and it forms a real image behind the primary mirror. The form of the secondary mirror in the Gregorian is that of an ellipsoid of revolution, the ellipse being a curve so constructed that an object at one of its foci will have a corresponding real image at the other focus. Consequently, in the Gregorian telescope, the two foci of the secondary mirror are at the principal focus of the primary mirror and at the final image-point, exactly as in the Cassegrainian form.

The Gregorian reflector gives an erect image, but, because of its very small effective field of view, it is not often used. It also affords a compact arrangement, although not as compact as the Cassegrainian. Fig. 96 shows the relationship of the curves for the Newtonian, Cassegrainian, and Gregorian forms.

160. The Schmidt Camera

A type of telescope which has been coming into prominent use is the Schmidt camera, which may be said to be a sort of combination reflector and refractor. Its principle is that of using a thin, aspheric lens to correct for the spherical aberration of a concave spherical mirror (fig. 97). The so-called *correcting plate* has a peculiar shape, indicated in the diagram, and does not form an image, but merely introduces spherical

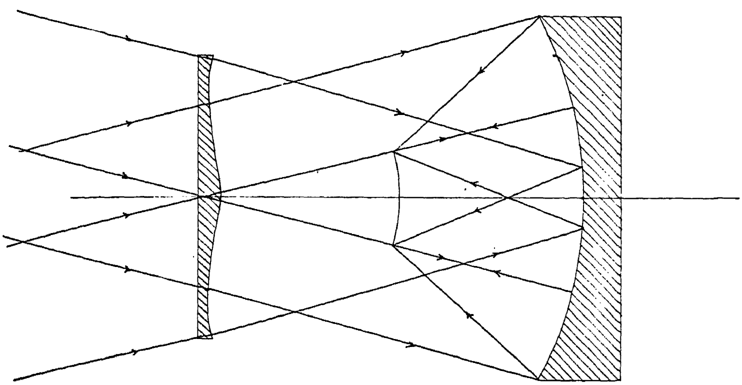


FIG. 97

Optical system of the Schmidt camera

aberration of equal magnitude and opposite sign to that of the concave mirror. The Schmidt camera may be made in very short focal lengths, giving good definition over a very wide field of view (15–20°), which is not possible with a paraboloidal mirror, the latter being especially subject to coma. The focal surface of a Schmidt camera is spherical and plates

or films have to be curved. As can be seen from the diagram, it is not feasible to use the Schmidt camera visually in its customary form, although some special optical arrangements have been devised to make this possible.

Schwarzschild has designed a two-mirror reflecting telescope giving a flat field of view, and Baker, Wright, and others have designed telescopes on the Schmidt principle with special features, but none of these is in common use at the present time.

CHAPTER XVIII

CAMERAS

161. Purpose

The invention of photography was not an optical one. The property of lenses in forming real images on a suitable screen was known for many years before a method was discovered of making a permanent recording of those images by treating the screen with materials within which light produces a chemical change. The camera is, however, an optical instrument, and we are interested in it from that point of view. The chemical properties of plates and films we shall touch upon briefly in (177).

162. Optical System

A camera really consists of only one optical element, the objective. The light-sensitive plate is placed in the focal plane of this objective, which forms a real image on it. In principle, therefore, the camera is the simplest of all optical instruments. The photographic objective, however, is one of the most highly developed products of the designer's art.

163. Principal Parts

The camera consists fundamentally of four principal parts: the *objective;* the *camera body,* containing a suitable device for holding the plate or film in the proper position; the *shutter,* whose purpose is to let light into the lens for the specific length of time necessary to record the image on the plate; and the *adjustable diaphragm,* the purpose of which is to control the amount of light entering the instrument, and which may really be considered a part of the optical system.

164. Focal Ratio and Speed

The most common method of describing the optical properties of a camera is to give its *speed* or *focal ratio,* which is the focal length of the objective divided by the aperture. The unit-area brightness of the image formed by a camera is increased by increasing the aperture (since the difficulty arising in the telescope (149) does not exist in a camera). If the brightness of the image increases, the time necessary to record it on the plate is decreased, hence the synonymity of focal ratio with speed. The symbol universally used for focal ratio is lower case f followed by a period or a virgule (/). It is essentially a statement of the focal length in units of the aperture. Cameras fall loosely into three groups, according to speed. Beginning with the fastest, we have the group containing the miniature cameras, press photographers' cameras, etc., designed to take pictures under all kinds of light conditions and frequently of moving objects, whose focal ratios range from f/1.5 to f/3.5. Secondly, there is the large group of general purpose cameras, including most hand and studio cameras, with focal ratios of from f/3.5 to f/8. And finally there is the class of cameras with focal ratios greater than f/8, which comprises most of those cameras used for special purposes where there is no lack of illumination and where exposures as long as necessary may be given. This group also includes the inexpensive "box" cameras.

The adjustable diaphragm, of course, permits changing the focal ratio as desired, with restriction to a maximum speed (168). The rating given to a camera always refers to the largest available opening of the diaphragm.

165. Photographic Objective Lenses

It can be readily seen that, because a photographic objective must cover a very wide field of view (usually about 50°), it is going to offer considerable difficulty with the oblique aber-

rations (chapter XIII). In fact, modern photographic objectives would be impossible were it not for a very important optical principle, namely, that in the case of a refracting surface, when the entrance pupil is located at the center of curvature, the conditions for axial and oblique bundles of light are identical, and the oblique aberrations vanish. It is possible to achieve this situation, of course, only for a single surface and a single point, but it is possible to achieve a close approximation of it in the case of a meniscus lens. The simplest type of camera objective consists of a single meniscus lens, mounted with its convex surface toward the plate, and with a diaphragm at such a point that the entrance pupil lies at the mean center of curvature of the two surfaces (fig. 98). Such a lens will give a satisfactory image at a focal ratio of f/8 or greater, but pictures taken with it cannot be satisfactorily enlarged to any considerable degree.

Another saving grace in the design of photographic ob-

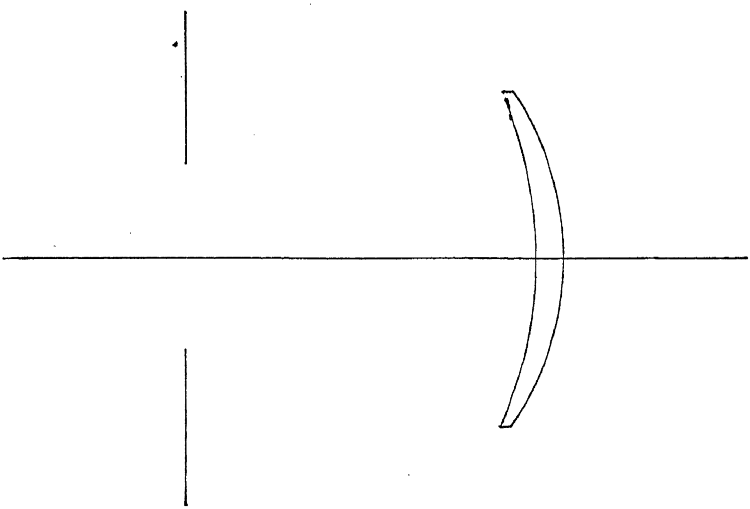


FIG. 98

Single meniscus lens

jectives is that the conditions to be satisfied with respect to all the aberrations are not nearly so strict as in the case of really good visual objectives. In a visual telescope, the eye can detect the fuzziness in the image introduced by circles of confusion of point-images as small as 0.1 mm. in diameter. In the case of a photographic objective, because the image is not examined under high magnification, and because the grains of the precipitated silver in the plate are of finite size, it has been found from experience that circles of confusion as large as 0.25 mm.* are usually acceptable in the final photograph. See below.

Another device customarily taken advantage of in photographic objectives is the efficacy of the combination of light flint and dense barium crown glass in reducing aberrations, as used in the Kellner eyepiece (134).

166. Modern Objectives

All really good photographic objectives approach the standard form of two meniscus converging compound lenses similar

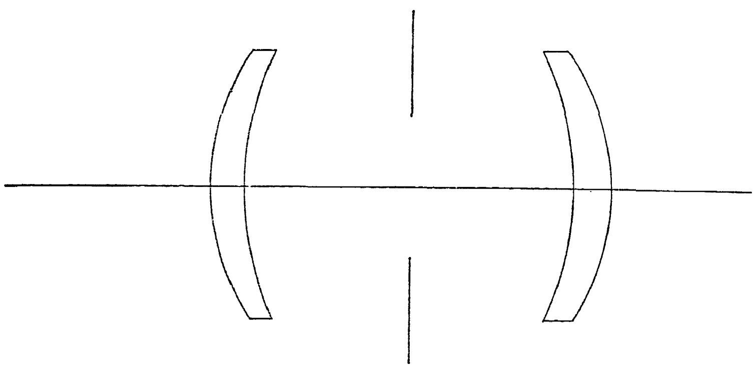


FIG. 99

Standard form of photographic objective

Both components are multiple in most cases.

* This is for ordinary cameras. For some photographic objectives, especially motion-picture camera objectives (where the image is to be enlarged many hundreds of times), the tolerance is much smaller.

(but not identical) to each other, with the diaphragm between, and the entrance pupil close to the mean center of curvature of each of the two components. The faster the lens, however, the stronger the tendency to depart from this form.

The principle followed is that of balancing the aberrations of one component against those of the other, since their opposed position (fig. 99) results in the oblique aberrations being of opposite sign. Fig. 100 shows a few well-known types of photographic objectives.

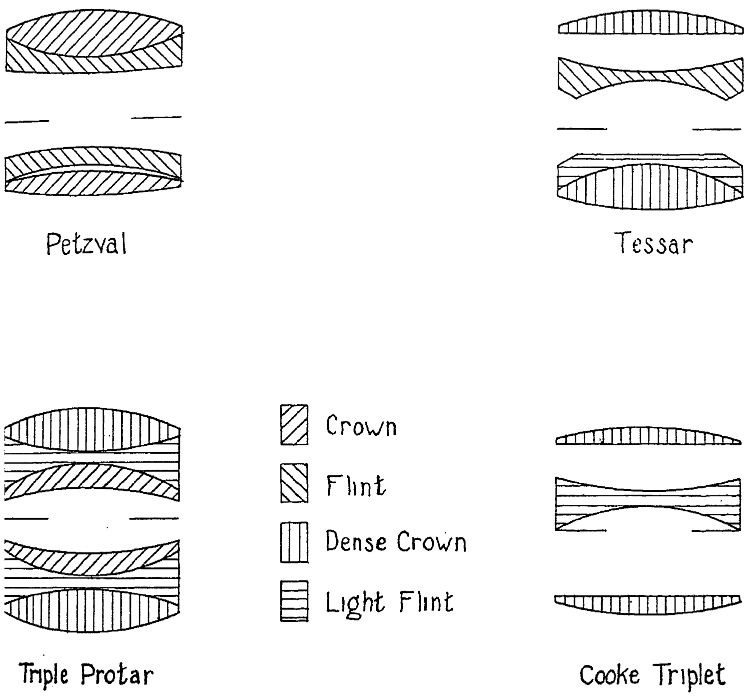


FIG. 100

Common types of photographic objectives

167. Depth of Focus

A very important concept in cameras is that of *depth of focus,* the range of distance within which the image is satis-

factorily sharp. A camera would be of little value if it would furnish a clear image only of objects at a specified distance from the lens and render blurred images of objects at all other distances. Now by definition (equation 15) the distance of an image from a lens depends strictly on the distance of the object. But, due to a tolerance in the size of the circles of confusion, there is a range of distance in front of and behind the true focal plane within which the circle of confusion of a point object is within the specified tolerance.

If the permitted size of the circles of confusion of a point image is x, the aperture d, the correctly focused object distance m, then the distance which may be added to m (t) and the distance which may be deducted from m (t′) are given by (appendix I):

$$t = -\cdot \frac{m^2x}{m'd + mx}$$

$$t' = -\cdot \frac{m^2x}{m'd - mx} \tag{34}$$

which depends upon the diaphragm opening, d, and consequently a reduction in this opening will increase the depth of focus. This geometrical analysis represents only one aspect of the problem. It was mentioned in (8) that geometrical optics is not sufficient to describe all optical phenomena. In particular, when questions of the exactitude of image-points are considered, geometrical optics may indicate results which are at variance with observed phenomena. In connection with depth of focus, the question of resolving power, discussed in (411), arises, and usually leads to an even greater tolerance for depth of focus than is given by the geometrical considerations discussed above, especially in cases of "slow" lenses.

The reduction in depth of focus with increase in the lens

diameter is one of the principal disadvantages of the faster lenses, and one thus finds them rarely in the larger cameras.

Recently, a motion picture camera lens has been designed in which one of the internal components is vibrated rapidly along its optical axis by an electromagnet, thus varying the focal length repeatedly over a predetermined range. In this way, objects at widely separated distances may be brought to a clear focus on the film several times during the exposure. These sharp images register on the film more rapidly than the blurred, out-of-focus images, and the result is a picture with equally good definition over a very wide range of object distance, although definition as a whole is somewhat poor, but not objectionably so.

168. The Iris Diaphragm

The adjustable diaphragm between the lenses is called the *iris diaphragm* from its resemblance, in appearance and function, to the diaphragm of the human eye. On cheaper cameras, it may be a series of holes of varying size, so arranged as to

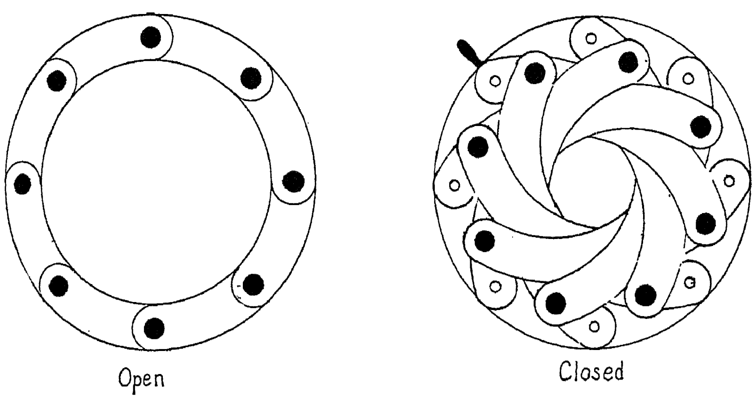


FIG. 101

Iris diaphragm

be rotated into position one by one. This is the arrangement in cameras using the single meniscus lens. In better cameras, it is a leaved affair (fig. 101) adjusted by the rotation of an outer ring. The rotating lever has an arrow which is read against a scale indicating the focal ratio of the camera corresponding to a given position of the lever. The diaphragm itself, of course, is located between the two components of the lens, as described in (166).

169. The Shutter

The shutter of a camera is for the purpose of permitting light to fall upon the light-sensitive plate for the correct amount of time, known as the *exposure*. All the better cameras have shutters designed to give a variety of exposure times as desired, ranging from 1/5 second to 1/1500 second.

There are two principal types of shutter, leaf shutters and focal-plane shutters. The leaf shutters work on a similar principle to the iris diaphragm, there being a number of leaves (usually five) which overlap over the opening, and, pivoting at the outside, open from the center. They are kept closed by a spring when not in use, and are operated by a lever and cam arrangement which permits them to stay open for a specific time. There are innumerable designs of operating mechanisms, one example of which is shown in fig. 102. The exposure time is set by means of a lever or a rotating ring with a suitable scale, indicating exposure time in fractions of a second. *Time* and *bulb* exposures are usually also provided, in the first case the shutter opening upon one depression of the operating lever and closing upon the next, in the latter, the shutter remaining open as long as the operating lever is held in the depressed position.

The focal-plane shutter is, as its name implies, located in the focal plane of the objective, immediately in front of the plate or film. It consists of a narrow slit which travels more

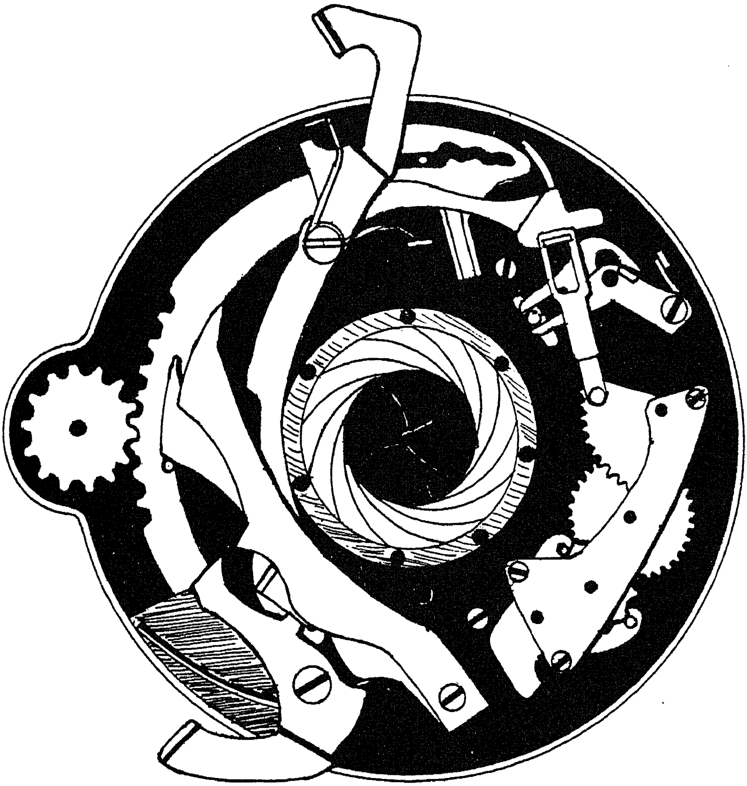


FIG. 102

Common leaf-type shutter mechanism

or less rapidly across the focal plane, exposing the plate in a continuous series of narrow strips.

Since the exposure time is merely the time necessary for the slit to travel its own width, the shutter mechanism does not have to work as rapidly as in the case of a leaf shutter, thus the focal-plane shutter is better adapted for extremely short exposures (faster than 1/500 second).

The focal-plane shutter has another inherent advantage in

that it permits the objective of the camera to be used as a *finder,* without removing the film or plate. The operator can then focus by means of a full-sized image (170).

170. Focusing Devices

If, in equation (34), we consider a camera of focal length of 100 mm. and an object at a distance of 3000 mm. (about 10 feet), we can show that, if the focal ratio is f/13 or greater, the depth of focus will extend from m/2 to infinity. In this case, for any object farther than m/2, no adjustment of the focus would be necessary. It is customary to make cameras whose focal ratios are greater than about f/11 of the *fixed-focus* type, in which the position of the objective is fixed with respect to the plate.

When the speed is greater, however, or when any camera is to be used on objects close at hand, it is necessary to change the distance between the objective and the plate. This is always done by moving the objective.

In many hand cameras, this adjustment is performed by rotating the front component of the objective on the mounting threads of its cell. An index point is provided on the camera body and a distance scale on the cell. Of course, this changes the separation of the lens components and has an effect on the quality of the image, but, since the separation is not critical with respect to aberrations, and the necessary motion is at most a few hundredths of an inch, the effect on the image is insignificant.

A better arrangement, from a theoretical point of view, is that provided on many folding cameras, in which the bellows (see 171) is compressed or extended to adjust for focus. In larger cameras, the objective is frequently mounted on a rack and pinion for focusing.

The correct adjustment is determined in one of two ways. In smaller cameras, not equipped with a focal-plane shutter, the usual arrangement is a distance scale on the focusing device.

When a really precise focus is necessary, however, this arrangement is not satisfactory, and one must focus by examining an actual image formed by the objective upon a ground-glass screen.

When the operator has plenty of time, this can be done by putting a ground glass in place of the plate and then, when the camera has been properly focused, putting the plate into position and making the exposure. When an exposure must be made hurriedly, however, and with a minimum of preparation, some method must be provided making it possible to examine a full-sized image with the plate in position. When the camera is equipped with a focal-plane shutter, a mirror may be placed in front of the plate position and the objective image formed upon a ground glass at the top of the camera body. Once the camera has been focused, the mirror is swung out of the way with a lever and the exposure is made. Such cameras are known as *reflex* cameras.

Another method used in some cameras is to provide two matched objectives in a common focusing mount, one being used for the picture and one for focusing. They need be matched only with respect to focal length. Both methods are shown in fig. 103.

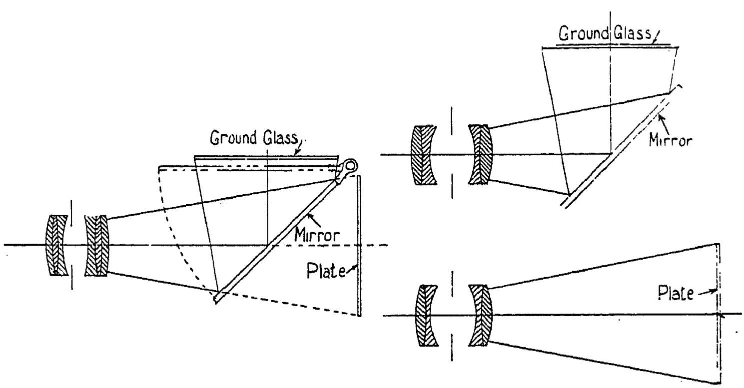


FIG. 103

Focusing devices used with focal-plane shutters

Some of the more expensive miniature cameras have a coupled range finder for focusing, in which a very simple type of coincidence range finder (chapter XXVI) is so mounted that the mechanism used for obtaining coincidence operates the camera-focusing device simultaneously. It is doubtful whether this device is any more accurate than the distance scale, however, since the error of a range finder of such short base (1 to 2 inches) would be comparable with errors of judgment for any reasonable distance.

171. The Camera Body

The function of the camera body is to hold the objective and the plate in their proper relative positions and exclude all light except that which enters through the objective. There are three principal parts to the body: the front, which holds the objective with its diaphragm, and the shutter and shutter mechanism (unless the shutter is of the focal-plane type), and contains the focusing device; the back, which holds the film or plate and in some cases a ground-glass screen for focusing, and contains the roller mechanism if roll film is used; and the frame or bellows, which shields the space between the objective and the plate from the entrance of any light. The cloth bellows, found in so many types of cameras, is provided in order to permit the camera to be folded up into a compact space when not in use.

172. View Finders

If the camera is focused by any other means than examination of a full-sized image on ground glass, the camera body will also contain one or more *view finders,* for pointing the camera in the proper direction and observing just what objects will be contained in the picture.

The commonest type of view finder is really a miniature telescope, with objective and eyepiece and usually a plane mirror interposed at an angle of 45° between them (fig. 104a). The

mirror acts as a field stop and is of such a size as to include the same field of view which is provided for in the frame holding the plate or film. An alternative method is to provide a ground-glass screen in place of the eyepiece in this type (fig. 104b).

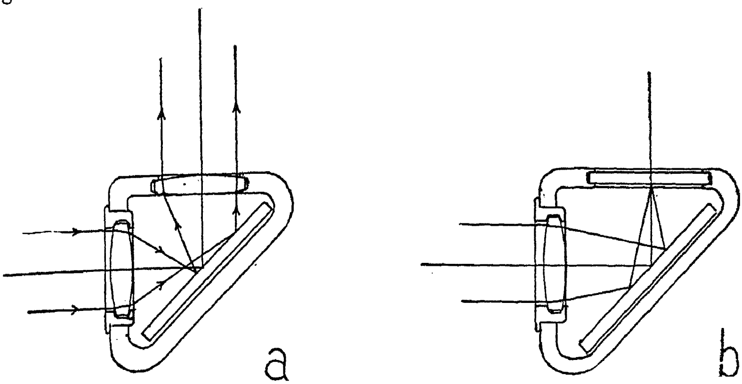


FIG. 104

Two types of view finder

a. Telescope type. b. Ground-glass type.

Another type frequently found is the direct-vision type, in which a frame and a pinhole are arranged to give the proper field of view when the eye is held close behind the pinhole. In this type, the camera must be held in front of the face when taking a picture, while in the case of the telescope type with right-angle deviation by the mirror, the camera is held at the waist and the operator looks down into the finder.

In the telescope type, either two finders are provided, or the one is adjustable so that a picture may be taken with the long dimension of the plate in either the horizontal or vertical direction. The reason for providing a rectangular frame for the plate or film is aesthetic; one merely prefers to see (or is more accustomed to seeing) rectangular pictures. Further, circular pictures would waste much of a roll of film.

173. Proper Distance for Viewing a Photograph

In order to secure the proper perspective in a photograph, it should be viewed from a distance equal to the focal length of the objective which recorded it (or x times that distance, if the photograph has been enlarged x times). Since the customary reading distance is 10–12″, it follows that a photograph will have correct perspective only if it was taken with a lens of this focal length. Most cameras have a much shorter focal length than this, and, therefore, most photographs have a somewhat distorted perspective. This is not usually sufficient to be immediately noticeable, but in the miniature cameras which have become so popular in recent years, the focal length of the objective is so short (1 to 2 inches) that the effect becomes quite marked unless the picture is considerably enlarged, and this constitutes one of the strongest objections to this type of camera.

174. Types of Cameras

The camera exists in a wider variety of forms than any other optical instrument with the possible exception of the telescope. Almost any visual instrument can be readily converted into a camera by increasing the distance between the eyepiece and the objective and placing a plate or film at the point where the resultant real image is formed, or, if the field of good definition covers a sufficient area, by merely placing a photographic plate at the principal focus of the objective. There are many cameras designed for special purposes, which it is not our intention to cover here. But in cameras designed for general use, there are a few distinct types.

The simplest and most inexpensive of cameras are the so-called *box* cameras, familiar to everyone, in which the body is in the form of a rigid rectangular box. These cameras possess, usually, single-meniscus objectives and have a choice of three diaphragm openings, f/11, f/16, and f/22. The view

finders are of the ground glass type. The shutter is merely a flat metal plate with a hole which swings in front of the lens. It has only one speed, usually about 1/30 second. Provision for *time* exposure is made. These box cameras are made in several sizes and customarily use roll film. Such a camera takes a satisfactory picture under proper lighting conditions, but the picture is not sufficiently sharp to permit very much enlargement.

Next in order of cost are the various familiar folding hand cameras, each provided with a cloth bellows between the front and back of the body to permit folding the camera into compact spaces when not in use. These cameras contain compound lenses of various designs, the maximum speeds available ranging from f/8 to f/3.5. They have iris diaphragms providing a continuous range of focal ratio down to f/32. They have leaf-type shutters providing for a variety of exposure times including time and bulb settings. The view finders are usually of the telescopic type, although the pinhole-and-frame type is sometimes found. Focusing is accomplished by varying the extension of the bellows or by moving the forward component of the objective on its mounting thread. These cameras are almost always adapted for roll film.

There is a group of larger cameras which is more adaptable for unusual conditions. They are usually collapsible, with bellows, but are almost always used with a tripod. They are furnished with the best lenses, of f/4.5 to f/2.5, and focus through the objective lens. Many of them have focal-plane shutters, and in all cases they provide a much larger range of exposure times. The bellows is usually extendable into an alternate position for pictures of very close objects. They are usually adaptable for plates. This group contains the photographers' studio cameras and press photographers' cameras. The adjustable iris diaphragm is, of course, present, allowing reduction of speed down to f/64 (fig. 105).

It should be noted that in cameras for special purposes there

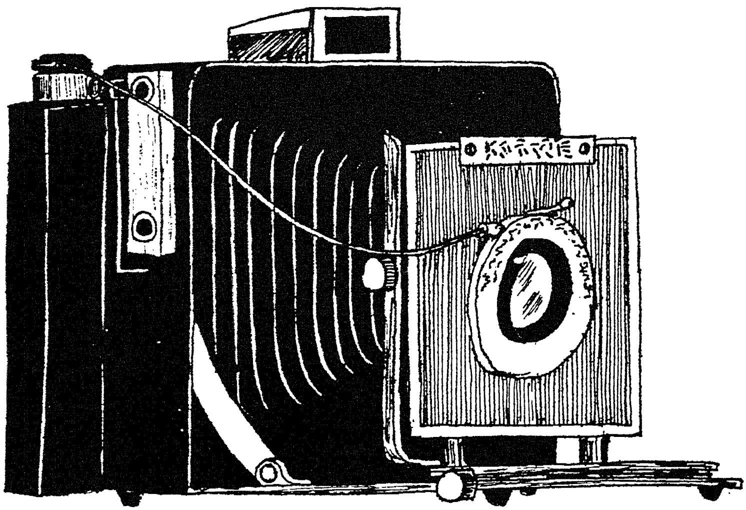


Fig. 105

Press Photographers' Camera

may be special objective lenses adaptable to those specific purposes. A good example of this is the *portrait* or *soft-focus* lens, in which definition is deliberately made poor in order to give a soft effect to the picture. Such lenses are useless for purposes where a needle-sharp image is desired.

Finally, there are the miniature, or *candid* cameras, which are very compact in size. They have, in most cases, very fast lenses, from f/4.5 to f/1.5, for taking pictures under all sorts of lighting conditions. They use motion picture film, 35 mm. in width, and take a great many exposures with one loading. The pictures are very small, and always require enlargement, since the focal length is usually about 1½ inches. A large range of shutter speeds is provided on leaf-type or focal-plane shutters, and various special attachments, such as range finders and built-in exposure meters (see 176) are to be found. Focusing is done by means of distance scale, or occasionally by coupled range finder (170).

In recent years, the recording of documents on *micro-film* has become increasingly popular. By this process, using special equipment, large size documents, pictures, etc., are photographed in reduced scale on a continuous roll of film, thus making it possible to file a large number of items in a very small space. Moreover, these films, if properly kept, will outlast the original documents. References can be made through the use of special projectors, and enlarged copies are simple to produce.

175. Operation of the Camera

There are four important steps in the operation of a camera, in taking a picture, which apply as definitely to the most elaborate and specialized photographic instruments as to the everyday snapshot camera.

The first is to aim the camera at the object or objects to be photographed. This seems too obvious to mention, but a large share of the poor photographs which have been taken are traceable to the inclusion in or exclusion from the field of view of important objects. This is where the camera which focuses with a full-sized image is at a decided advantage; it is difficult to tell with a small view-finder just what the picture will look like.

The second step is to focus the camera. If the camera focuses through the objective, this is merely a matter of moving the objective in and out until the image is sharp and clear. In fine work, however, it is well not to depend upon the eye's judgment, as to whether or not the image is exactly in the plane of the plate, in cameras where the ground glass focusing screen is in the exact position occupied by the plate during the exposure. There are two methods of making a more accurate placement of the image. One is to examine the image on the ground glass with a suitable magnifier. The second is the *parallax* method (367). For this method, the ground glass must be ruled with a few fine lines on the surface where the image is to be formed. When the image appears to be sharp, the eye is moved slightly

from side to side (or up and down) and the relation of the image to the ruled lines is observed. If the image appears to shift back and forth with respect to the lines, there is parallax, and the image and the lines are not in the same plane. If the *image* shifts in the same direction as the observer's eye, the image lies beyond the screen from the observer; if it shifts oppositely to the eye, it is closer to the observer than the screen. This is probably the most sensitive method of focusing. If desired, the parallax and magnifier method can be combined.

If the camera focuses by a distance scale, it is necessary to either measure or estimate the distance from camera to object. Usually, due to the depth of focus tolerance (167), judgment will be sufficiently accurate, but if the distance is only a small multiple of the focal length of the camera, and a large diaphragm opening is used, it will be far better to measure the distance. In a fixed-focus camera, of course, no focusing is necessary. It must be remembered that in the case of fixed-focus cameras, there is a minimum object distance (about 50 times the focal length); for less than this the camera will not give a sharp image.

The third step in operating a camera is the choosing of the proper diaphragm opening or *stop*. In most ordinary cases of picture taking, a large depth of focus is desirable, and, since the smaller the opening the greater the depth of focus, it is a good rule to use the smallest possible stop opening consistent with a reasonably short exposure time. This has the additional advantage of reducing the aberrations of the objective lens, therefore, making for a more perfect image. Occasionally, it is desired to concentrate upon a given object in the picture, and to produce a blurred background and foreground, and in such cases a wide opening will accomplish the desired results. However, this does not often occur, except to the professional, and he already knows far more than is stated here, so it is reasonable to say that it is only under the most unusual lighting conditions (or when pictures of moving objects are

to be taken) that it is ever found necessary to use a diaphragm opening wider than f/4.5, and only occasionally will it be necessary or desirable to use a wider opening than f/8. The proper openings for the large majority of snapshots are f/11 and f/16.

The final factor is the exposure time. This has three determinants: sensitivity of the plate or film being used, diaphragm opening, and illumination of the object. Sometimes the character of the object being photographed has a bearing on the exposure time, for instance, if the object is in motion, the exposure must be short enough to *stop* the motion, to prevent the image from moving across the plate. An exposure of 1/200 second is sufficiently rapid for most occasions and most cameras.

All manufacturers of films and plates include circulars in their film cartons giving tables of recommended exposure times corresponding to various diaphragm openings and conditions of illumination encountered in ordinary photography; it would, therefore, be useless to go into the matter deeply here. There are, however, two important facts to remember: first, that the effect of a change in diaphragm opening affects the exposure time by the *square* of the focal ratio, since the amount of light entering the lens is proportional to the *area* of the lens exposed. If the diaphragm opening is decreased by one-half, say from f/8 to f/16, the exposure is increased four times, say from 1/100 to 1/25 second. Secondly, the *character* of the illumination is as important as its intensity. The human eye reacts in an entirely different way to light than does a photographic plate; indeed, different types of films and plates react in quite different ways (177), and the camera user is strongly advised to adhere closely to the methods of judging illumination recommended by the manufacturers.

176. Exposure Meters

A much more satisfactory and safer way of determining exposure times is by the use of an exposure meter. Two types

are available. The wedge type, which is merely a wedge of translucent glass, etched with numerals, is the simplest. It is held between the eye and the object to be photographed, and the highest numeral which can be clearly seen is noted (fig. 106). A more accurate (and more expensive) type contains

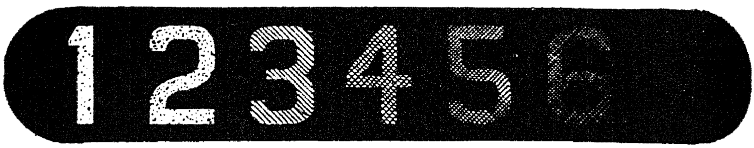


Fig. 106

Wedge-type exposure meter

a photoelectric cell and an indicator needle. This type is held as close to the principal object to be photographed as possible without blocking off the illumination, and the reading is noted (fig. 107). Tables are provided with both types which, by

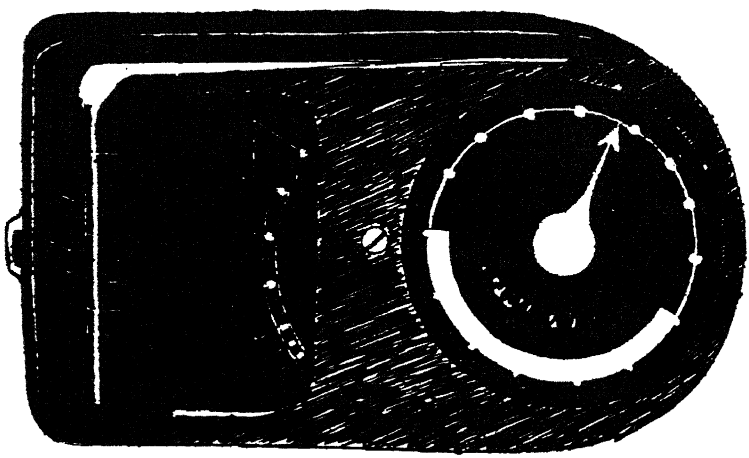


Fig. 107

Photo-electric exposure meter

means of numerical factors applied to film and diaphragm opening, readily determine the proper exposure time. Some of the more expensive miniature cameras have built-in exposure meters of the wedge type.

177. Plates and Films

The operating principle of the light-sensitive coating (emulsion) on photographic plates and films can be stated in a few words. Some chemical compounds of silver (e.g. silver bromide) are unstable, and the action of light energy dissociates the molecules into their constituent atoms. A plate or film coated with an emulsion containing certain forms of these compounds is exposed to the real image formed by the objective lens. This image is a pattern of light and shadow, and where light falls, its energy is partially absorbed by the chemicals in the emulsion and a number of molecules are dissociated, the number depending upon the intensity of the light in that vicinity.

The film is then placed in a chemical bath known as a *developer,* which combines with the bromide or iodide part of the molecule and leaves the silver as a precipitate on the plate or film. The action of the developer must be accurately timed, or eventually it will precipitate out *all* the silver in the emulsion. The silver in the molecules which received light energy are precipitated out first, however, and if the action of the developer is stopped at the proper time, by placing the film in a second bath, an acid known as *hypo,* which neutralizes the developer and dissolves the unused molecules, the result is an exact copy, in silver grains, of the image originally cast upon the emulsion.

This copy is, of course, in reverse; spots which were bright in the image are dark in the film. This is a negative. If, however, an emulsion-coated paper is exposed to an image formed of this negative, a *positive* copy will be produced. If it is desired to have a positive *print* the same size as the nega-

tive, a *contact print* is made, by holding the negative against the sensitized paper in a suitable frame and exposing it to light for a specified time. If the positive is to be of different size, the negative is mounted in a projector (see chapter XXI) of suitable form and an image of the negative is formed upon the sensitized paper.

This explanation is all that can be attempted here. The development of photographic emulsions has been the life task of hundreds of research workers, and a proper coverage would fill a library.

Photographic emulsions may be grouped into two main classes, *slow* and *fast*. The principal distinction between these, outside of their speed, is grain size, the size of the smallest groups of silver atoms deposited. Obviously, no detail smaller than the size of the grains can be registered, regardless of the qualities of the lens; and it is futile to enlarge photographs beyond the point where the grains show distinctly. Fast emulsions have a relatively large grain size and, therefore, photographs taken with such emulsions are likely to suffer in definition. In slow emulsions, however, the grain size can sometimes be kept so small that it is below the resolving power of the objective lens which then becomes the determinant for definition. Since the resolving power of a lens (411) increases with the diameter, the faster lenses have an additional advantage here.

Various degrees and varieties of sensitivity to color are available. Most modern films, either fast or slow, are *panchromatic;* the greater sensitivity of ordinary emulsions to the shorter wave-length light in the blue and violet region of the spectrum has been largely (but not completely) overcome, and photographs taken with panchromatic emulsions reproduce most nearly the naked-eye appearance of objects with respect to *value* (relative apparent brightness of colors). More specialized types of sensitivity to certain regions of the spectrum are available, principally in the slow emulsions.

Recent years have seen an unprecedented increase in the variety and sensitivity of the films and plates offered for general use. Many of the newer types were developed for professional requirements and were in use in laboratory work for some time before they were offered to the public. The fastest films available for popular use today are many times faster than any that could have been had 10 years ago. The faster types are still not available in the more popular sizes of roll film, although cameras using these sizes do not have fast lenses and thus are just the cameras which would benefit most from faster emulsions. It is true, however, that many of these cameras are not sufficiently light tight to permit the use of highly sensitive emulsions, nor are most amateur photographers sufficiently competent.

178. Filters

The properties of photographic emulsions are taken best advantage of through the proper use of filters. A filter is a pair of plane-parallel sheets of glass between which has been mounted a colored gelatin; some filters, however, are a single sheet of colored glass. The purpose of a filter is to regulate the relative intensities of the various colors of light which fall upon the emulsion. A yellow filter, for example, will hold back most of the blue and violet light to which the emulsion is most sensitive, and, therefore, permit the emulsion to give the same degree of prominence to the yellow and green areas in the object as would be given by the eye.

Many kinds of filters are available, including *neutral* filters, which merely decrease the *amount* of light entering the lens without varying its color distribution. Most of the very best examples of the photographic art have been made possible only through the judicious use of filters.

179. The Motion Picture Camera

The motion picture camera, in an optical sense, is identical with any other general type of snapshot camera. It merely is different in a mechanical way, being adapted to take exposures automatically in rapid succession on contiguous areas of a continuous film. Usually 16 exposures are taken each second, the mechanism being so devised that each portion of the film (frame) is halted in place before the lens while the exposure (usually 1/30–1/100 second) is made. The film then advances the proper amount, bringing the next frame into position, before the shutter reopens (fig. 108).

In *sound* motion pictures, a narrow strip at the side of the film is used for the *sound track,* which is exposed to a light regulated through a microphone system and varies either in width or intensity, depending upon which of the two principal methods of sound recording is used.

For viewing the motion picture, a projector (chapter XXI) is used, the film being run through at the same speed (16 frames per second) it ran through the camera. The eye is not sufficiently keen to detect such a rapid change of picture and thus the object in the pictures appears to be smoothly in motion. The sound track runs in front of a source of illumination, and the varying intensities of illumination transmitted through it are picked up by a photoelectric cell and the impulses converted back into sound.

Professional motion picture film is 35 mm. wide. Film used in the samller cameras sold for amateur use is 16 mm. wide. Recently, 8 mm. film has come into favor for amateur use, the camera recording the pictures on one-half of a 16 mm. film which is then reversed in the camera and the other half exposed. When developed and printed, the film is cut lengthwise down the center and run continuously through the projector. The popularity of narrower films is, of course, a

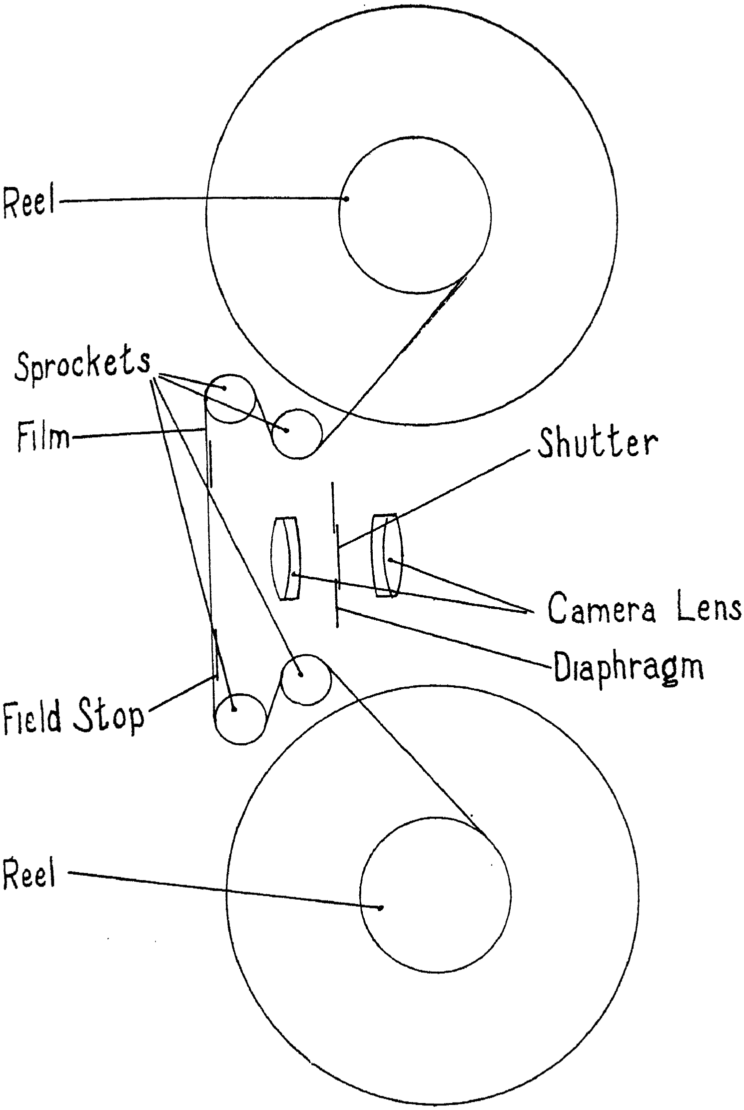


FIG. 108

Schematic diagram of the motion-picture camera

matter of expense, the operating cost being less, and the small diameter lens being much cheaper.

180. Color Photography

Ordinary photographs are in black and white. The recording of images in color requires the use of several different emulsions, usually three, one for each separate color which is to be recorded. During development, each layer of the emulsion develops in its own color only, and the combination gives a picture in full color, since, as any artist will explain, any known color can be produced by mixture from three primary colors; *red, yellow,* and *blue.* Several processes are available, which differ in detail, but not in principle.

It should be remembered that, although the speed of color films is much greater than when they were first available, even these so-called fast color films are still only about as fast as the slower ordinary black-and-white film. This means that color photographs can be taken only under conditions of brilliant illumination, and even then only with fairly lengthy exposures. Only the faster lenses (above f/3.5) can be successfully used for color motion pictures.

181. Telephoto and Photomacrographic Lenses

Several different types of auxiliary lenses are provided for attachment to cameras. The only two really important ones are the telephoto and the photomacrographic lenses.

The *telephoto* lens (fig. 109) is adapted for taking pictures

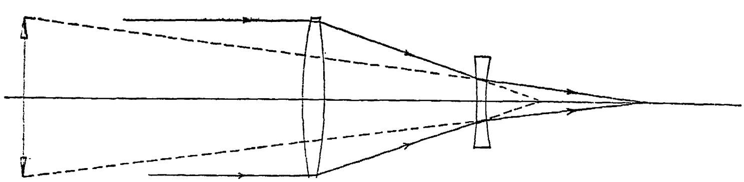


FIG. 109

The telephoto lens

of objects at a distance, and magnifying their images on the film over the size which would be produced by an ordinary objective. It is nothing more nor less than a lens of long focal length, which gives, of course, a larger image (and a smaller field of view). Any long focal-length lens would accomplish the same purpose, but in the telephoto lens the distance from objective to focal plane (back focal length) is considerably less than the equivalent focal length. As was described in (78), the telephoto lens is a combination of a converging and a diverging lens, so placed that their separation is greater than the algebraic sum of their focal lengths, the equivalent focal length being positive and becoming smaller as the separation increases. The negative component, of course, has the longer individual focal length. Fig. 109 shows the position of the equivalent thin lens.

The *photomacrographic* lens (fig. 110) is an ordinary converging objective corrected for rather short object distances. Its purpose is to provide an enlarged image on the film or plate of a relatively close object. In this respect, its problems are almost identical with those of a projector (chapter XXI). Such lenses usually provide magnification from 10 to 15 diameters. This type of lens is used in enlarging cameras, for making enlargements of photographic negatives.

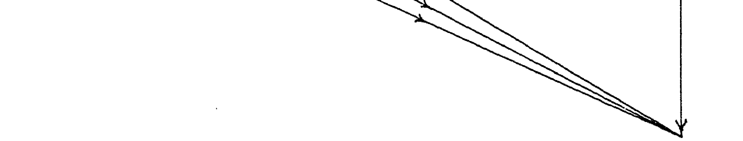


FIG. 110

The photomacrographic lens

CHAPTER XIX

THE MICROSCOPE

182. Purpose and Function

In chapter XVII we defined a telescope as an instrument for viewing distant objects. We can define a microscope as an instrument for viewing close objects. We saw (12) that in order to increase the apparent size of an object we bring it closer to the eye, but there is a limit set by the accommodation of the eye upon the closeness we can achieve. This is the near point of the eye, in normal eyes about 10 inches or 25 cm. away. If we can bring an object much nearer to the eye than this and then, by means of suitable optical aid, form an image of this object at a convenient viewing distance, without decreasing its apparent size, we can make it appear much larger that it would appear at a distance of 10″ and thus be able to discern finer detail within it.

In the case of the telescope, we had exactly this problem in dealing with the real image formed by the objective, and we solved it by introducing an *eyepiece.* This eyepiece formed a virtual image at a convenient viewing distance (preferably infinity). Therefore, the eyepiece of a telescope is in reality a microscope. Negative eyepieces, of course, do not qualify in this respect, since in this case the object is virtual.

183. The Simple Microscope

The simple microscope is an instrument which performs this function with a single optical system. Usually the simple microscope goes under the name of magnifier or magnifying glass, and telescope eyepieces (positive) fall into this category when considered apart from the rest of the instrument.

The simplest microscope is, of course, a single converging lens. If a real object is placed at the principal focus of such a lens, the light emerges from it in parallel bundles, and the lens may be said to form a virtual image at infinity. If the object is placed just within the principal focal plane, a virtual image is formed at a finite distance in front of the lens. The ideal or *normal* case is where the image is formed at infinity, as in the case of a telescope in normal adjustment. In this case, the apparent size of the image to an eye placed behind the lens is the apparent size of the object as seen from the primary principal plane of the lens, which may, of course, within certain limits, be made as large as desired by making the focal length of the lens sufficiently short.

184. Magnification of the Simple Microscope

The magnifying power of the telescope was shown (145) to be the ratio of the apparent size of the object to the apparent size of the image seen through the instrument. Since the objects were considered to be at infinity, their apparent sizes at the eye and at the objective of the telescope were the same. But in the case of the microscope, the objects are at finite distances, therefore, a standard distance at which apparent size to the eye is taken is necessary to define magnifying power. This distance is 10 inches, or, 25 cm., approximately the distance of the near point of the normal eye.

Now, if the apparent size of the image formed at infinity by a simple microscope is equal to the apparent size of the object as seen from the (principal plane of the) lens, the ratio of the apparent size to the eye at 10″ to the apparent size from the lens is evidently the ratio of 10″ to the focal length of the lens, or:

$$m = \frac{10}{f} \tag{35}$$

where f is the focal length of the simple microscope.

185. Types of Simple Microscope

As telescope eyepieces (positive) are really simple microscopes, the various types of solid oculars listed in chapter XV are really different types of simple microscopes, and it is needless to enumerate them here again. Three types are shown in fig. 76. The most useful form of simple microscope is the solid sphere, and the first two combinations shown in fig. 76 are of this type, the two external curves being struck from the same center. The central diaphragm and the compound form both serve to reduce aberrations.

Since the maximum diameter a spherical lens of given radius of curvature can have is twice this radius, as the required focal length becomes shorter and shorter for higher magnification, the size of the lenses diminishes rapidly until they become so small that they are difficult to mount and even more difficult to manufacture, and restrict the field of view severely. Moreover, the *working distance,* in the simple microscope, the front focal length (72), reduces to impracticable dimensions. With any form other than the solid sphere, the aberrations become unmanageable as the magnification increases.

186. The Compound Microscope

The only way to avoid these many difficulties is to construct the microscope as a compound instrument, containing (at least) two optical systems with special and individual functions. Although the modern compound microscope exists in a bewildering variety of forms and functions, and may cost anywhere from a few dollars to a few thousand dollars, all modern compound microscopes are functionally identical in their optical systems. The only differences are in the quality of the lenses, the degree of magnification attainable, and especially in the quality and variety of the accessory equipment.

187. Optical System of the Compound Microscope

The compound microscope is very like a telescope in that it consists of two optical systems, objective and eyepiece, the first of which forms a real image in the focal plane of the second, which in turn produces a virtual image at infinity. The difference lies in the fact that, in the case of the microscope, the objects to be examined lie at a finite (and usually very small) distance in front of the objective. The object is placed just outside the principal focal plane of the objective, which, being a converging lens, forms, therefore, a real image at a considerable distance (with respect to the focal length) behind the lens. This image, further from the lens than the object (79), is much larger, and if this image in turn is placed in the focal plane of an eyepiece (simple microscope) of relatively short focal length, the resultant magnification of the compound system may reach extremely high values.

Fig. 111 shows the optical system of a compound microscope, with objective and eyepiece indicated merely by their principal planes, because the variety of forms in which these optical systems are found does not permit drawing a representative form. The diagram differs from those found in most volumes on the microscope in that the image formed by the eyepiece

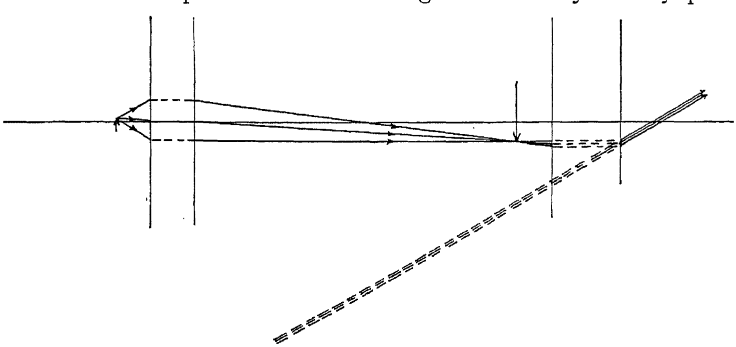


FIG. 111

Optical system of the compound microscope

lies at infinity, that is, the rays emerge from the eyepiece in parallel bundles. As in the case of the telescope, the normal eye should find this condition the most convenient and restful. However, due to physiological and psychological eccentricities of the individual, most observers will adjust the instrument so as to form a virtual image at approximately the near point of the eye (10″). This is the situation most usually represented in schematic drawings of the microscope (and the telescope in many cases). It does not give a true conception of the optical functions of the instrument, nor does it permit an absolute determination of the magnification, since if the virtual image is formed at a finite distance, then the position of the eye behind the eyepiece will have an effect on the magnifying power. *Magnification is always stated on the assumption that the instrument is so adjusted as to render parallel bundles of light to the eye.*

Considering the instrument as a single compound optical system, we see that the object lies in its anterior focal plane, which requires that the light emerge in parallel bundles. The aperture diaphragm is inside the objective, and the field stop is provided, as in a telescope, in the anterior focal plane of the eyepiece.

The magnifying power is evidently going to depend, not only on the focal length of the objective and eyepiece, but also on the position of the object with respect to the focal plane of the objective, or, what amounts to the same thing, the separaion of objective and eyepiece. This is usually about six inches, and is a standard with the manufacturers.

188. Magnification of the Compound Microscope

The linear magnification produced by the objective is given by equation (23) as:

$$m_o = -\frac{x'}{f'_1}$$

and we have already stated (equation 35) that the magnification of the eyepiece (which is a simple microscope) is:

$$m_{\Delta} = \frac{10}{\cdot}$$

and if we now put Δ as the separation between the posterior focal plane of the objective and the anterior focal plane of the eyepiece (the *normal* adjustment), we have $x' = \Delta$, and the product of the magnifications of the two systems becomes:

$$M = -\frac{1\Delta}{f'_1 f_2} \tag{36}$$

where $1 = 10$ for inch measurement and $1 = 250$ for millimeters.

Interchangeable objectives and eyepieces are usually stamped with the magnifying power, and the magnification of the combination is given by the product of the two. We see from the negative sign in the above equation that the compound microscope gives an *inverted* image.

189. The Numerical Aperture

The optical efficiency of a microscope is measured by a quantity to which Abbé gave the name *numerical aperture.* It is:

$$A = n \sin \eta \tag{37}$$

where η is half the angular size of the entrance pupil as seen from the object and n is the index of refraction of the medium in which the object lies. This quantity determines the permissible magnification by controlling the *resolving power* (194).

Since η cannot possibly be greater than 90°, $\sin \eta$ can never be greater than 1.0, and thus, if the object lies in air ($n = 1.000$), A can never be greater than 1.0, and from a practical point of view can never quite reach this value. For A greater than

1.0, n must be greater than 1.0, which means that the object must lie in a medium other than air. For this reason, all high-power objectives are *immersion* objectives (a drop of liquid is placed between the object and the objective). Immersion objectives use, generally, water or oil of cedar, whose indices of refraction are 1.3 and 1.5, respectively. Some immersion objectives have a numerical aperture as great as 1.4.

190. Microscope Objectives; Design

The microscope objective is one of the most complex of optical systems. Having a wide field of view and an extremely large aperture, it presents very difficult problems for the optical designer, in the removal of aberrations. Further, the aberration tolerances are vanishingly small, for the image presented to the eyepiece must be as nearly perfect in every respect as it is possible to make it.

The optical principle around which the microscope objective is designed is the principle of *aplanatic points.* For any spherical refracting surface, there exist two conjugate points such that an object at one of the points will be imaged without axial spherical aberration or coma at the other. These points are known as the *aplanatic points* of the surface (fig. 112). If properly designed, any optical system can be made aplanatic (free of spherical aberration and coma) for a pair of such points, *but for one pair and one pair only.* Obviously, in the case of the microscope, this pair of aplanatic points is going to be the pair represented by the object on the slide and the image produced by the objective. Since the separation, Δ, of objective and eyepiece affects the location of these object- and image-points, it follows that Δ must remain fixed and invariable. This is the reason that focusing of a microscope is done by moving the entire optical system with respect to the object under examination.

The most important work to be done by the optical designer on microscope objectives is to remove, so far as is possible,

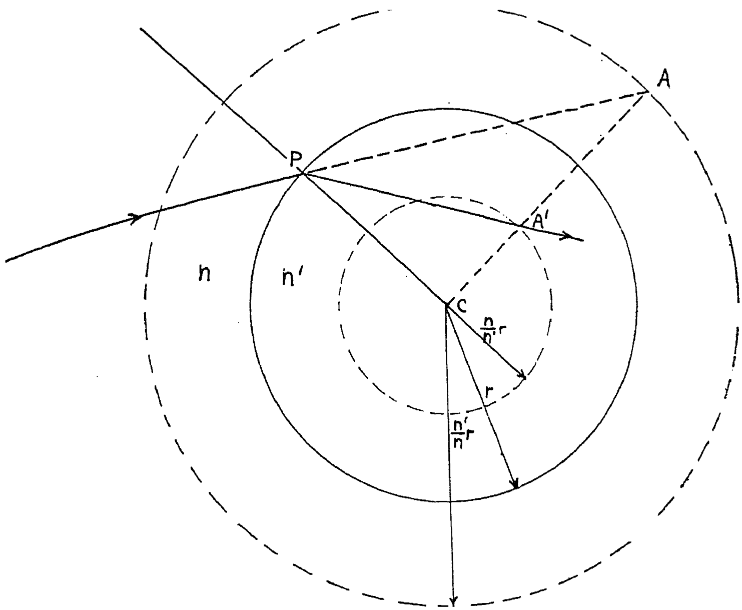


FIG. 112

Aplanatic points of a spherical surface

aberrations resulting from chromatic differences (of spherical aberration and magnification) over the whole range of the visible spectrum. Special optical glasses have been of invaluable assistance to him in the last 50 years.

There are three commonly used types of microscope objectives: 1. Simple achromatic, usually consisting of a pair of well-separated achromatic lenses. These are corrected chromatically for two colors (usually F and C) and spherically corrected in one color (usually D); 2. Semi-apochromats, or *fluorite* objectives. These have a better correction than the achromats, because of the use of fluorite, which has decided advantages as an optical medium in the removal of the secondary spectrum; 3. Apochromats, which usually contain a great

number of components, are chromatically corrected for three colors and spherically corrected for two. It should be remembered that microscope objectives are corrected for a specific value of Δ and, while it is possible to achieve reasonable good results when using an objective with a microscope tube for which it has not been designed, the value of Δ may be slightly

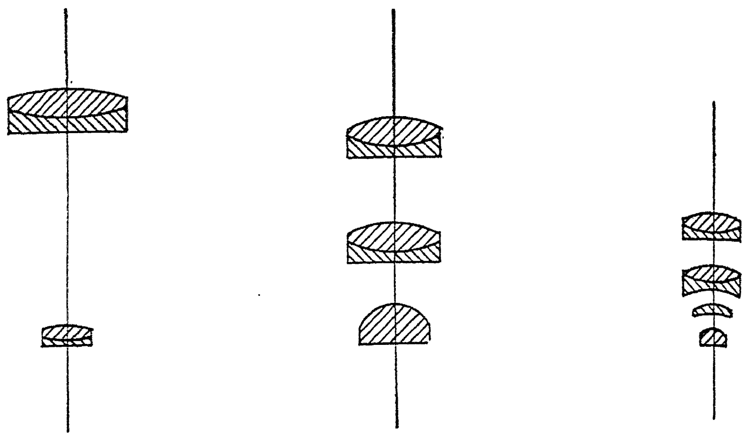


FIG. 113

Common designs of microscope objectives

different, although the tube length (198) is standard, in the instruments of different manufacturers, and the best possible results require that the objective be used in the tube for which it was designed. Fig. 113 shows examples of the three common forms of objective.

A more important point is that microscope objectives are corrected for a specific thickness (usually 0.17 or 0.18 mm.) of cover glass (200) and *will not work properly with any other thickness*. This is especially important with the shorter focal length objectives. A change in the thickness of the cover glass requires a change in the value of Δ, and, although some microscopes are made with adjustable tube length to correct for

this discrepancy, these instruments are not commonly in use, and in any case should be adjusted only by an expert microscopist.

191. Microscope Objectives, General

Microscope objectives are interchangeable, often mounted in sets of three or four on a revolving *nosepiece* so that the desired one may be quickly brought into play. On each objective cell will be found stamped the focal length, the numerical aperture, and the *power* (indicated by X), which is the ratio of the size of image to the size of object, the linear magnification. Objectives are furnished in a variety of focal lengths, from 1.5 mm. to 64 mm., the powers varying from about 1.0 to 100. The more commonly used values of the focal length are: 64 mm., 40 mm., 32 mm., 16 mm., 8 mm., 4 mm., 1.8 mm., 1.5 mm. The longer focal length objectives (above 32 mm.) are almost always achromats. The fluorite and the apochromat objectives rarely appear with a longer focal length than 8 mm., because the more perfect corrections are usually not necessary with the lower magnifications.

Those objectives with a focal length less than 3.0 mm. are almost invariably immersion type objectives, because the higher magnifications require that the numerical aperture be very great (189) and it is impossible for the numerical aperture to be greater than 1.0 for a *dry* objective. Immersion type objectives *must* be used with a drop of the liquid *for which they were designed* between the objective and the cover glass.

Frequently, the 16 mm., 10X objectives are made *bifocal;* the lower component can be removed to give a 32 mm., 4X objective. The lower component is sometimes mounted on a swinging cell for quick changes, and in such cases it is called a *stirrup* objective. This makes for a saving in the cost of objectives and makes it possible to put four different magnifications on a 3-place nosepiece. The definition of such objectives in the 32 mm. form is never, however, as good as that of a

standard 32 mm. fixed objective, although sufficiently good for routine work.

192. Eyepieces

Microscope eyepieces are usually marked with the power, on the basis of equation (35) for a simple microscope. 6X, 10X, and 25X are usually found, the 10X being by far the most frequently used; it is customary in microscopes to change objectives rather than eyepieces when a change in magnification is desired.

There are three general types of microscope eyepieces in common use, which are in no way different from telescope eyepieces (see chapter XV). The Huygenian is the most popular, because of its better correction for transverse chromatic aberration, but when a reticle is to be used, the Ramsden type gives better results (132). Reticles are, however, frequently used with the Huygenian. Also, there are *compensating* eyepieces, made by various manufacturers. In the case of apochromat objectives, there are small residual aberrational errors which can be eliminated through the use of an eyepiece which has been designed to give equal discrepancies of opposite sign. These eyepieces are designed for use with specific objectives, that is, the apochromat objectives of a particular manufacturer, and care should be taken to make sure that objective and eyepiece are made by the same concern. The fluorite objectives are also usually improved by the use of compensating eyepieces. Compensating eyepieces should always be used with apochromatic objectives, as the ordinary eyepieces will not correct for the residual aberrations that it was necessary to leave uncorrected in the apochromats.

There is so little variation among manufacturers in the lower magnification objectives, and in the Ramsden and Huygenian eyepieces, that they may be used interchangeably.

Certain eyepieces, known as *wide field* or *high eye-point* eyepieces, are furnished for use by individuals who must wear

spectacles while using the microscope. If one is affected by ammetropia, it is better not to wear glasses while using an optical instrument which has a focusing arrangement (153), but in the case of a microscope, the method of use often requires frequent shifting of the eye from instrument to a note pad and back, in which case ammetropic observers must often wear glasses in order to make notes satisfactorily. In any case, observers affected with astigmatism must wear their spectacles when using an instrument. Since the usual eye distance on microscope eyepieces is about 4 mm., an observer wearing spectacles will have his eye too far from the eye lens, and thus will have his field of view severely restricted. Wide field eyepieces are made with an unusually great eye distance so the observer wearing spectacles will obtain full advantage of the field of view.

When the microscope is to be used for photography, it is well to use an eyepiece especially designed for this purpose. Such eyepieces are corrected for the distortion and curvature of field shown by ordinary eyepieces used out of normal position to project a real image at a distance (about 10″).

193. Tube Length

A quantity closely associated with the value of Δ is the *tube length,* or distance from the top of the tube to the shoulder against which the objective cell rests in the nosepiece or adapter. In most instruments of American manufacture, this distance is a standard 160 mm. (for one manufacturer, 170 mm.). In English microscopes, the tube length is usually 10″. It should be clear that an objective designed for use in an instrument with a tube length of 160 mm. will not be quite as satisfactory in a tube of different length, due to the disturbance of its aplanatic points, although it can be used in it with a consequent change in the working distance of the objective and the magnification. In any case, in a difference of 10 mm., the loss in image quality will not be strongly evident.

194. Resolving Power

The *resolving power* of a microscope is, as in a telescope, the separation of two points which the instrument is just capable of forming into two distinct images. In the telescope (411) the measurement is angular, and expressed in seconds of arc. In the microscope, the measurement is linear, representing the actual separation of the two points on the microscope slide. It is given by:

$$d = \frac{\cdot}{2A} \tag{38}$$

where λ is the wave-length of the light used, and A is the numerical aperture (189). The visible light which appears brightest to the eye (yellow-green) has a wave-length of about 5500 Angstroms, or about 0.00055 mm. Hence, the highest possible resolving power for a *dry* system is about 0.6 micron (1 micron = .001 mm.) while an oil-immersion objective with a numerical aperture of 1.4 will reach 0.2 micron. In photography, light of shorter wave-length than visible light (ultraviolet) may be used to give a somewhat greater resolution. Fused quartz lenses must be used throughout (as one finds in a spectroscope), to make the most effective use of the shorter wave-lengths.

As with the telescope, there is no point in enlarging an object beyond the power of the instrument (and the human eye) to reveal fine detail within it. The only effect is to render the entire image indistinct. For this reason, the maximum practicable magnification with a microscope is 800 to 1000 times the numerical aperture of the objective. Therefore, the limit of microscope magnification may be set arbitrarily at about 1500 diameters. In photography, by using light of shorter wave-lengths, we can do somewhat better.

There is another factor here, also. In dimensions smaller than a micron, we are approaching the order of smallness of

the wave-length of light as well as that of atoms and molecules. Light can never reveal the details of an object very far below its own wave-length, and if we could perceive individual atoms and molecules (which we can never do with light) the structure of the object would disappear completely. The world of molecules is threatened with invasion by the electron microscope, which instrument is not really optical and, therefore, is beyond our scope.

195. Construction of the Microscope

The microscope consists of five distinct parts: the *base,* upon which the instrument rests; the *arm,* usually pivoted in the base and permitting the tilting of the instrument; the *body,* which is attached to the arm in sliding ways, and which carries the optical system; the *stage,* attached to the arm, upon which the specimen is mounted; and the *condenser,* beneath the stage, which concentrates light upon the specimen to be examined. The cheaper microscopes of low power do not usually have condensers, but depend solely upon the mirror to give the proper condensation of light (fig. 114).

The mirror, which is used even with the condenser, has a plane side and a concave side. The radius of the concave side is such as to make its principal focus lie in the plane of the specimen on the stage. When a condenser is used, the plane side of the mirror is always used.

The arm is usually semicircular in shape, carrying the stage at one end and the body at the other, and is attached to the base at a point near the stage. It is usually mounted on a pivot, with a clamp, so that the body and stage may be tilted at a convenient angle for observation, or be held vertically if the specimen is such that tilting is undesirable. The arm carries the body in sliding ways in which it may be moved up and down on a rack and pinion for focusing (190). This rack and pinion is known as the *coarse adjustment* mechanism. There is also a *fine adjustment* mechanism which carries the

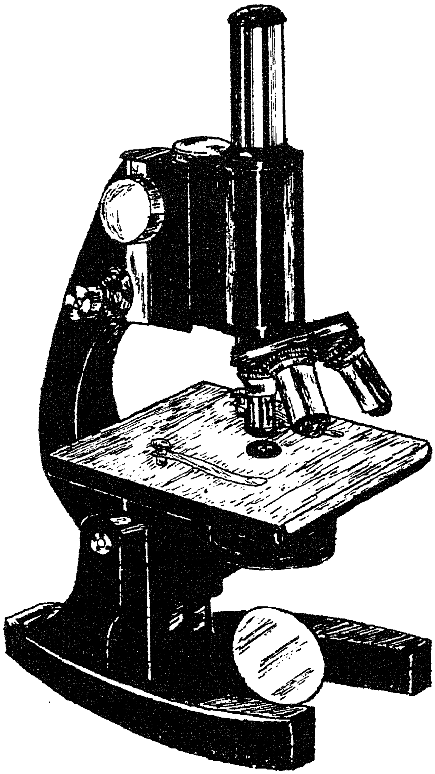


FIG. 114

The microscope

body up and down over a small range by means of a cam and spring arrangement. This fine adjustment is necessary for focusing under high power, when the tube must be moved a matter of a few microns.

The body carries the optical system, that is, the objective and eyepiece. It is customary to provide a revolving nosepiece in the better microscopes. This nosepiece carries from two to four objectives, and rotates about an axis at an angle to the tube, so that any objective desired may be brought into play

by a partial rotation of the nosepiece. The objectives are mounted in threaded cells and may be secrewed into the nosepiece, or into a *single nosepiece adapter* which, in turn screws into the body of the microscope. The eyepieces usually fit in a smooth sleeve at the top of the tube, and are also interchangeable.

The stage is a flat plate perpendicular to the optical axis of the microscope, and carries the slide upon which the specimen is mounted. There is a central hole for admission of light from the condenser or mirror below. On the simpler types of microscopes, the slide is merely held on spring clips. More elaborate instruments will usually have a mechanical stage, which provides for moving the slide about in front of

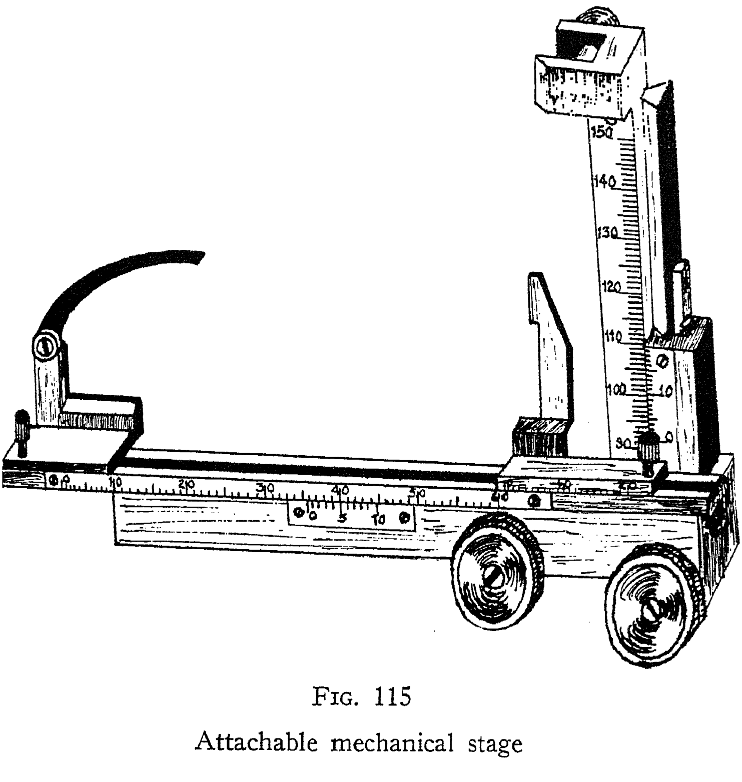


Fig. 115

Attachable mechanical stage

the objective by means of adjusting screws. Usually, but not always, these mechanical stages have scales and verniers for measuring purposes (fig. 115). Sometimes rotating stages are provided, and when this is done, the optical axis of the microscope must be carefully aligned upon the center of rotation of the stage. Some special microscopes are equipped with *universal* stages, which provide for rotation about a horizontal as well as a vertical axis. All stages have a central hole to admit light from the condenser or mirror. The condenser is discussed in (197).

196. Illumination

It is clear that in order to examine an object under high magnification, it must be brilliantly illuminated. It is not sufficient merely to expose it to diffuse light, it is necessary to focus a brilliant spot of light upon it. For this reason, microscopes are provided with equipment for concentrating light upon the object to be examined. In the simpler types, with low magnification, the concave mirror collects light and focuses it upon the specimen. When the magnification is not too high, it is usually sufficient to collect light from the sky through a window. If this is done, care must be taken to see that no external objects, such as trees or buildings, are focused in the plane of the object by the mirror, as its details will obscure the specimen. The purpose is to get even illumination over the objective's entire field of view of sufficient intensity to disclose minute details. It is also important to obtain light from a sufficiently wide angle to make use of the full numerical aperture of the objective being used. The test of this is to remove the eyepiece and examine the rear surface of the objective. If it is completely filled with light, then the full numerical aperture is being used. It is also important not to have too much light, else the resultant glare will ruin the definition of the image.

When high magnification is being used, a condenser (197)

is necessary. In this case the *plane* side of the mirror is used. It is usually better to use a microscope lamp as a source of illumination even when the condenser is not being used, as this provides even, constant illumination, and devices are provided, such as iris diaphragms and filters, so that the intensity of the light may be properly adjusted.

When the object to be examined is opaque, the illumination must come from above, and here *vertical* illuminators (199) are frequently used, although it is sometimes sufficient to direct a microscope lamp at the specimen from a convenient position. In top illumination, the angle from which the illumination comes may be very important.

All in all, *illumination is one of the most important aspects of microscopy,* and cannot be overemphasized. Innumerable elaborate accessories are available for various types of illumination. All of these are useful in their proper place, and many are indispensable for certain kinds of work.

197. Condensers

A microscope condenser is an optical system designed to furnish a concentration of light upon the specimen. Most condensers are achromatic, in order that the colors in the specimen may be properly rendered. Many are very highly corrected, containing as many as six elements. Condensers are usually provided with an iris diaphragm for controlling the numerical aperture, which must be equal to that of the objective being used.

The condenser, with its mounting, is attached to the arm beneath the stage, and the entire assembly is frequently referred to as the substage. The condenser is adjustable on a rack and pinion for proper focusing, which is as important for a condenser as for an objective. Fig. 116 shows a common type of condenser.

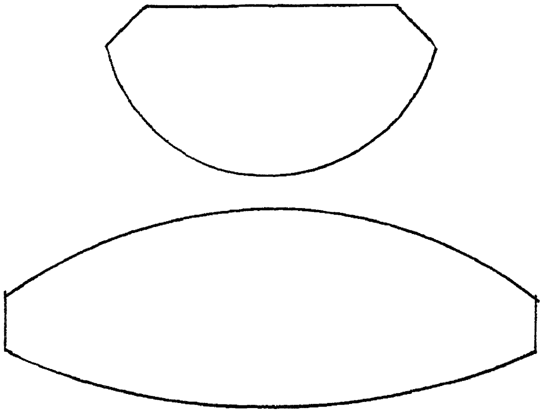


FIG. 116

Optical system of a simple type of condenser

198. Dark-Field Illumination

If the light from the condenser enters *only* at an angle greater than the numerical aperture of the objective, the light passes *across* the field of view, which is, therefore, dark. The only light which can then enter the objective is light scattered from particles in the field of view. By the use of this *dark-field* illumination, particles as small as 0.004 microns can be detected, far beyond the resolving power of the microscope. Of course, the objective cannot form a sharp image of such particles, but from their appearance certain inferences can be drawn as to their properties. This type of illumination is also valuable in observing transparent bodies, and is essential in much bacteriological work.

The condenser used for dark-field illumination is of a special type, within which a few minor variations may be found. Fig. 117 shows the path of the rays in a dark-field condenser. These condensers are very carefully made and *must be used with a slide of the correct thickness.* For dark-field work,

the illumination must be very strong. Since dark-field illumination depends essentially on the fact that the numerical aperture of the condenser is greater than that of the objective, care must be taken to see that the objective is stopped down with its diaphragm if the rated numerical aperture of the dark-field condenser is less than that of the objective. Since most such condensers have a rated numerical aperture of from 0.85

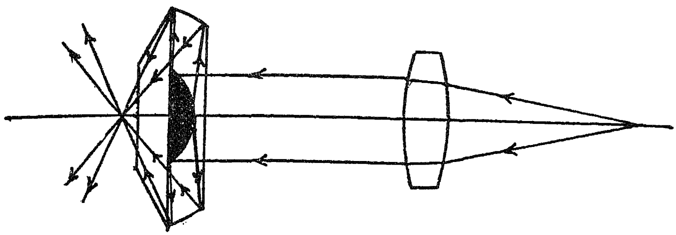


FIG. 117

Dark field condenser
(Shown in horizontal position)

to 1.0, most oil-immersion objectives must be stopped down before using them for dark-field work.

199. Vertical Illuminators

When the specimen is opaque, the illumination must come from above, and when an ordinary microscope lamp is insufficiently strong, or when oblique lighting will not suffice, it will be necessary to use some sort of *vertical illuminator*. The principle of vertical illumination is that the light reaches the specimen down the tube of the microscope. There are two methods by which this is done. In the more elaborate type, a ring of light from a special condenser is made to travel down the tube outside the objective cell, and is focused upon the object by means of an annular lens surrounding the front lens of the objective. In the simpler forms, the objective itself is made to act as condenser by placing either a prism or a plane-parallel plate just above the rear lens of the objective,

this prism or plate reflecting light down through the objective. With the prism, only about half the objective is available for forming the image at the eyepiece, while in the case of the plate, considerable light from the illuminator is lost.

Vertical illuminators are usually attached to the tube of the microscope in the objective adapter, and contain a threaded well to receive the objective. Fig. 118 shows the three types.

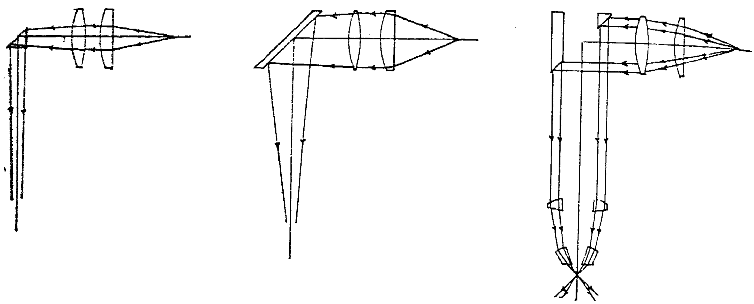


FIG. 118

Three types of vertical illuminator

200. Preparation of Specimens

The microscope is a very specialized instrument, and can be used only under very specific conditions. We have seen that it is necessary to go to a great deal of trouble in illuminating the specimen. It is also necessary that the specimen to be examined be prepared very carefully for observation, or the microscope is useless.

Transparent specimens must be no more than 8–10 microns in thickness, and 2–5 microns is preferable. Such thin slices are produced with a *microtome,* a device similar to a butcher's slicing machine, but, of course, far more precise. Even with such a machine, it is a matter of considerable skill to slice these very thin sections, and frequently the material from which the specimens are to be cut must be frozen or embedded in a special material in order to slice readily. Embedding material is

usually paraffin or celloidin, although in recent years, the synthetic resins, notably methyl methacrylate and its associated compounds, are coming into prominent use. Sections of hard materials, such as rock or metal, must be ground and polished very carefully.

These sliced specimens are mounted on *microscope slides,* thin, rectangular glass plates (standard dimensions: 3″ x 1″) and then covered with a *cover glass,* which is cemented to the slide. The objective of the microscope, as was stated, is corrected for the thickness of the cover glass, which must be optically finished and held to a thickness tolerance of 0.01 mm. In the case of a dark-field condenser, the slide itself must be of correct thickness. Cover glasses are usually 0.17 to 0.18 mm. thick, slides, 1.10 to 1.45 mm. Many specimens must be *stained* with one or more special types of stain in order that the details may become visible against the background.

When opaque objects are to be examined under vertical illumination, it is not necessary to use sections, but it is usually necessary to prepare a surface on the specimen for examination, and to make sure that the specimen is mounted in such a way that this prepared surface is exactly perpendicular to the optical axis of the instrument.

201. Using the Microscope

Let us assume we are making an examination of a specimen with a microscope, and briefly outline the procedure. We have a microscope equipped with a substage condenser, a lamp, a revolving nosepiece containing four objectives, a 4X, 32 mm., a 10X, 16 mm., a 45X, 4 mm., and a 100X, 1.8 mm., oil-immersion objective, a 10X eyepiece, and a mechanical graduated stage.

We place the slide on the stage and arrange our illumination by adjusting the iris diaphragms on the lamp and perhaps using filters. We first use the 32 mm. objective, giving a magnification, with the 10X eyepiece of 40X. It may be necessary to

remove the top lens of the condenser in order to illuminate the entire field of view of this low-power objective. We bring the objective to its approximate working distance (185), about one inch, before looking into the instrument and then, with our eye in the proper position (about 4–5 mm. above the eye lens), we bring the object into sharp focus with the coarse and fine adjustment mechanisms, making sure that the fine adjustment mechanism is in the center of its movement before we start. Next, we remove the eyepiece and make sure that the back of the objective is just filled with light by looking down the tube and adjusting the iris diaphragm of the condenser until the proper condition is attained. Some readjustment of the illuminator may be necessary to give just the proper amount of light.

We are now ready to make an examination of the specimen under 40X. We note a portion of the object which we wish to examine under higher magnification, and we bring it exactly to the center of the field of view, using the mechanical stage adjustments. The field of view decreases as the power increases, and if we did not bring this interesting part into the center of the field, it would probably not be in the field at all when we changed objectives.

We now change to the 16 mm. objective by revolving the nosepiece, replacing the top lens of the condenser and refocusing it, and then bring the objective to its working distance (about 6 mm.). After focusing, we again remove the eyepiece and check the back lens of the objective for optimum illumination and proceed to examine the specimen under 100X. Again we bring the most interesting part to the center of the field before proceeding to the next objective.

We go through a similar procedure with the 4 mm. objective, which gives us 450X, checking the back lens of the objective each time and adjusting the condenser diaphragm as the numerical aperture of our objective increases. Also, we must not forget to bring the most interesting part of the object directly

into the center of the field of view by means of the mechanical stage before proceeding to the next higher power.

Our last objective is the 1.8 mm. oil-imersion system. We first place a drop of the required kind of oil (usually oil of cedar) between the top lens of the condenser and the bottom of the microscope slide. We then place another drop of oil upon the cover glass, and carefuly lower the objective into it *before putting our eye to the eyepiece.* We then *focus with the fine adjustment.* If we use the coarse adjustment on a high-power objective with our eye at the eyepiece, we will go past the point of clear focus without realizing it and are almost sure to screw the objective down against the cover glass, cracking it and perhaps damaging the objective itself.

With the oil-immersion objective in place, we must adjust the illumination very carefully for good results. We are now examining the specimen under a magnification of 1000X, which is about as high as it is practicable to go.

If we wish to make measurements, we place a suitable reticle in the eyepiece and/or use the mechanical stage adjustments. If we wish to refer to a particular portion of the specimen at some future time, we bring it to the center of the field of view and then mark the readings of the stage micrometers on the slide itself. It can then always be placed back on the instrument in the same position.

202. The Binocular Microscope

Microscopes are frequently made binocular, that is, with two eyepieces. The binocular microscope must not be confused with the stereoscopic microscope (203), for binocular microscopes have only one objective and do not give the two different fields of view necessary for stereopsis (208). Binocular microscopes exist solely for the increased comfort of the operator, which is a really important factor when the instrument is used steadily for a considerable period of time.

In all binocular microscopes, the light from the objective is

divided by a set of prisms into two beams, one to each eyepiece. The two fields of view are, therefore, identical and there can be no stereoscopic effect. There are two types of binocular microscopes, parallel-tube and converging-tube. Which is the better is entirely a matter of the individual user. The parallel-tube type is used with the eye muscles relaxed, the two eyes looking along parallel lines. This would theoretically be more restful, but some individuals have great difficulty in relaxing their eyes to this extent. Fig. 119 shows the optical system.

The two tubes of the binocular microscope are movable to facilitate changing their separation to fit the interpupillary distance of the observer. The exit pupils of the two eyepieces should be exactly the same distance apart as the pupils of the observer's eyes. Since this varies from 56–72 mm. with different individuals, the instrument must be made adjustable in this respect. The movement must be such that the length of the light path through the instrument will be the same for both tubes. The eyepieces used in binocular microscopes must be carefully matched with each other with respect to magnification.

The usual arrangement for dividing the light beam is a combination of two right-angle prisms immediately above the objective. These prisms separate the light into two beams. Each of these beams then enters a right-angle prism and is reflected up the proper tube to the eyepiece. Inclined bodies are sometimes furnished on binocular microscopes, so that the objective is vertical for the examination of liquids, etc., this being made possible through the use of another prism between the dividing set and the objective. The prisms, of course, must be adjusted with great care so that the two fields of view coincide, avoiding *double vision* and consequent severe eyestrain on the part of the observer.

Because the light is now divided between two images, and in addition because of light absorption in the prisms, the il-

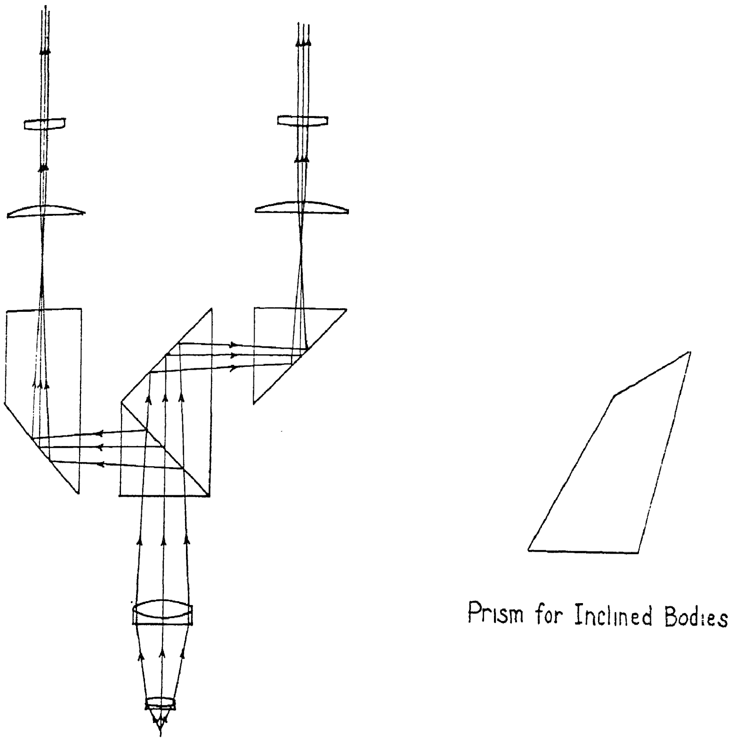


FIG. 119

Optical arrangement of the binocular microscope

lumination must be much greater in a binocular microscope than in a monocular instrument.

In the case of the binocular microscope, there is usually an arrangement for individual focusing of one of the eyepieces. The non-adjustable eyepiece is focused in the usual way, by moving the tube on the coarse and fine adjustment mechanisms, and then the second eyepiece is focused to the individual eye. The two eyes of a given individual are apt to differ slightly in optical characteristics, making individual focusing necessary.

203. The Stereoscopic Microscope

The *stereoscopic microscope* is designed to give a stereoscopic view of the object under examination. It has two objectives, very carefully matched and centered, mounted to converge at their normal working distance. Actually, the stereoscopic microscope is two independent microscopes (fig. 120).

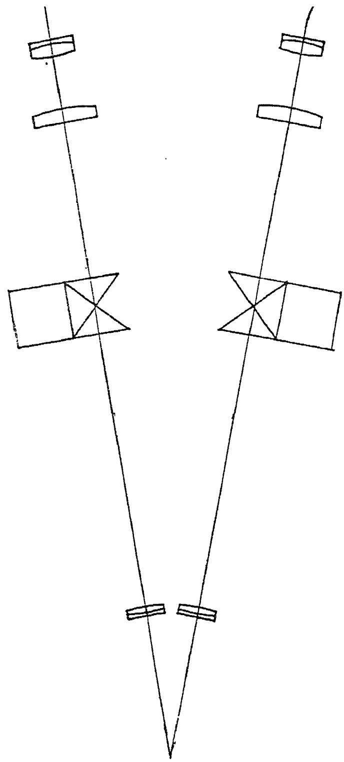


FIG. 120

Optical system of the stereoscopic microscope

Because this microscope is frequently used for dissections, it is sometimes called a *dissecting microscope*. It contains

erecting systems, almost invariably of the Porro prism type shown in fig. 74.

Stereoscopic microscopes have the same adjustments for interpupillary distances and individual focusing adjustments as are found in regular binocular microscopes. Because of the short working distance of high-power objectives, making it impossible to mount them so as to converge on the field of view, stereoscopic microscopes rarely if ever provide for greater magnification than 150X.

204. Inverted Microscopes

In the examination of the surfaces of objects, such as rocks or metals, it is advantageous to use the *inverted microscope.* In this instrument, the objective points *upward,* and the specimen is placed with its prepared face *downward* on the stage. This makes the surface perpendicular to the optical axis and avoids the necessity of finishing the opposite side. Also, much larger blocks of material can be used as specimens (fig. 121).

In the inverted microscope, the tube of the instrument is mounted at a 45° angle to the vertical, and a reflecting prism is placed in the elbow to turn the light up the tube.

205. The Polarizing Microscope

In the examination of crystalline mineral specimens, much can be accomplished through the observation of their effect upon polarized light. For this reason, the *polarizing microscope* has come into much prominence in recent years. A full discussion of the subject of polarized light is beyond our scope, but it is covered briefly in chapter XXXIII.

The polarizing microscope is an ordinary microscope with a few additional features, indeed, these features may be obtained and attached to the ordinary microscope with satisfactory results. These consist of the polarizer, the analyzer, the Bertrand lens, and attachments for the insertion of *retardation plates* in the optical system (fig. 122).

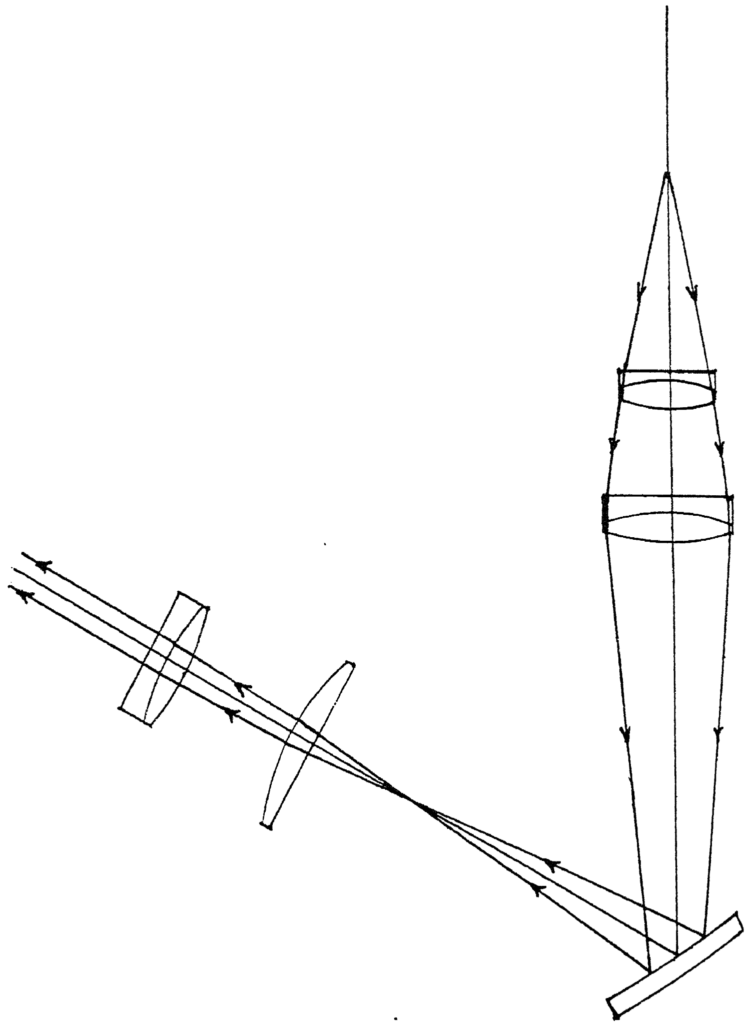


Fig. 121

Optical system of the inverted microscope

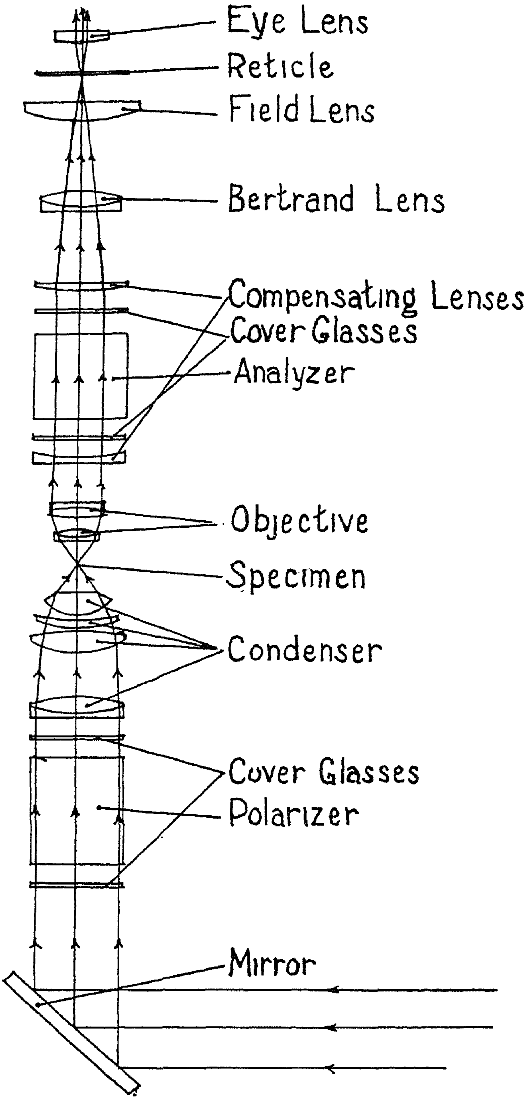


FIG. 122

Optical system of the polarizing microscope

The polarizer and analyzer are identical, consisting of a device for producing polarized light from a beam of unpolarized light. The most effective ones are composed of calcite prisms, cut in a specific way. These prisms are usually protected by cover glasses. The polarizer is located in the condenser, and delivers polarized light to the specimen. The analyzer is in the tube of the microscope.

The polarizing microscope must be equipped with a rotating stage with a graduated scale, and either the polarizer or the analyzer (preferably both) must rotate about the optical axis on a scale. The retardation plates are used for the purpose of producing interference patterns from certain materials. This interference pattern (chapter XXXIII) occurs upon the rear surface of the objective lens. The Bertrand lens makes it possible to focus the eyepiece directly upon this pattern.

The optical elements of polarizing microscopes must be absolutely strain-free, a condition not usually found to a precise degree in ordinary microscope objectives, and this means that polarizing microscope objectives must be specially procured.

The polarizer, analyzer, and Bertrand lens are mounted so as to be readily swung into and out of position, so that the instrument may, if desired, be used as an ordinary microscope. All optical parts must be very carefully centered and the axis of rotation of the revolving stage must coincide with the optical axis of the instrument. The polarizing microscope requires many times as much light as an ordinary microscope.

206. Microcomparators

The comparison microscope, or microcomparator, might be said to be a binocular microscope in reverse. It has two objectives but only one eyepiece. This eyepiece has a divided field of view, one half representing the view of one objective and the other half that of the other. By manipulation of the mechanical stages, similar parts of two objects (such as bullets)

may be brought side by side in the field of view, and matched up, if matching is possible (fig. 123).

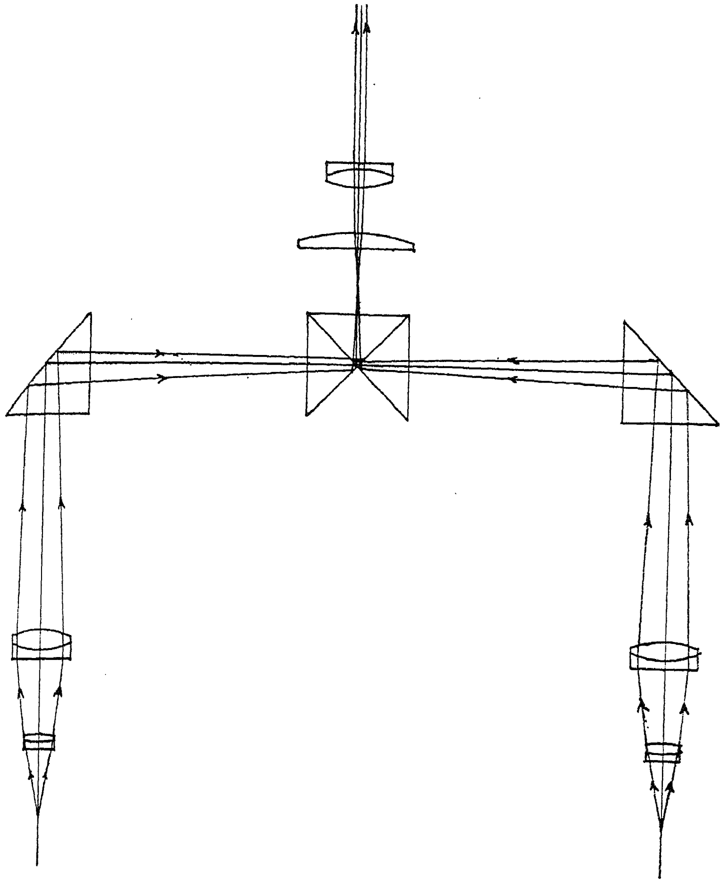


FIG. 123

Optical system of the microcomparator

A variation of the ordinary microcomparator is the *blink microscope*, used by astronomers to examine plates of star fields. Two plates of the same region of the sky, taken at different times with the same objective are placed under the

miscroscope objectives. Here the two fields are superimposed and not divided as described above. The two plates are then alternately illuminated in rapid succession. Any star whose position has changed during the interim between exposing the plates will appear to jump back and forth. If the star has changed in brightness during the period, it will appear to wink. Asteroids, variable stars, and stellar proper motions are detected with the instrument.

207. Photomicrography

It is a simple matter to make photographs of the specimens on microscope slides. The microscope tube is focused so as to form a real image on a screen at a suitable distance from the eyepiece, which requires that the microscope tube be raised. Photomicrographic cameras do not contain lenses, but are merely light-tight boxes which can be fastened over the eyepieces of the microscope and which hold a plate in the proper position. Focusing is done either on a ground glass at the focal plane or through an eyepiece and prism arrangement at the side of the camera head (fig. 124).

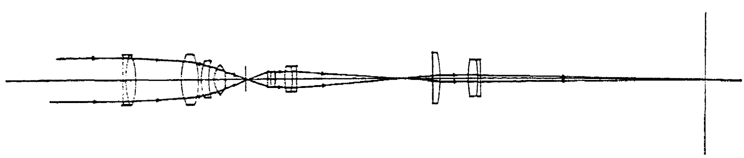


FIG. 124

Optical arrangement for photomicrography

Ordinary cameras may be used to take microphotographs by focusing the microscope for a virtual image at infinity, focusing the camera for infinity, and attaching it to the eyepiece of the microscope so as to exclude outside light. A picture may be taken through a telescope in the same way.

A great deal of illumination is necessary in photomicrog-

raphy, and exposures are usually of several seconds duration. It is desirable to use apochromatic objectives, especially designed for images in color. Special photomicrographic eyepieces are available, which correct for the curvature of field and distortion which is present when the image is projected on a screen by an ordinary eyepiece.

If the plate is 10″ from the eyepiece, the magnification of the photograph is equal to that of the microscope used visually with the same objective and eyepiece. This magnification may be increased or decreased by changing the distance from eyepiece to photographic plate and readjusting the focus.

Photomicrographic cameras should not be confused with photomacrographic cameras (181), the latter being merely cameras with special lenses for photographing close objects with considerable (about 15X) linear magnification.

CHAPTER XX

Field Glasses and Binoculars

208. Stereopsis

When we look at an object with both eyes, the direction of the object for each eye is slightly different than that for the other, and so the two retinal images are not in exactly the same position. Further, since one eye sees a little way around one side of the object and the other eye a little way around the other side, the images on the two retinas not only differ in position, but also differ slightly in appearance.

As a result of these two differences, we can perceive *relative distance* and make an unconscious estimate as to *form*. This is known as *stereopsis,* or depth perception. It is not entirely clear whether the difference in position or in appearance of the two retinal images is the major factor in stereopsis, or whether the muscular tension of the eyes converging on a given object has any noticeable bearing on the sensation. Stereoptic testing instruments frequently use cards upon which letters are slightly displaced for one eye with respect to the other, and here the subject can obtain stereoptic effect, although the letters are on a flat background and no aspect of *form* can enter the picture, so it would appear that the major factor is the apparent displacement of objects with respect to each other for the different positions of the two eyes. Experiments, however, seem to indicate that after proper training, individuals can perceive a *difference* in convergence angles as low as four seconds of arc, far below the resolving power of the eye and much less than the separation between two retinal cells.

Without going deeply into the matter, we can adopt the premise that stereopsis is a result of binocular (two-eyed) vision, that is, of the fact that the lines of sight from eyes to object *converge*. It is easy to see that the stereoscopic power will be proportional to the angle of convergence. Since this will decrease with the distance of the object and increase with the separation of the eyes, it follows that stereoscopic power varies inversely as the distance and directly as the separation of the eyes. The range at which stereoscopic power vanishes is the point where the angle of convergence has become so small that the eye is unable to detect any difference from parallelism in the lines of sight, and this is put, empirically, at the distance where the angle of convergence has become 30″, or about 500 yards.

209. Stereoscopes

Stereopsis is taken advantage of in the stereoscope, an instrument for viewing photographs taken with a stereoscopic camera. The stereoscopic camera has two objectives, separated by some suitable distance, and simultaneously takes two photographs of an object from slightly different points of view. The printed photograph is placed in the stereoscope, which is so constructed (fig. 125) that one eye sees the picture taken with one camera lens and the other eye the one taken with the other. This duplicates the situation which would have been presented to the eyes had they been placed at the points where the camera objectives were placed, and the objects in the photograph stand out in sharp relief. It is quite possible, with practice, to observe a stereoscopic photograph without the aid of the instrument, but this is difficult, since it requires conscious control of the convergence of the eyes.

If the lenses of the stereoscopic camera are separated by a greater distance than 64 mm., the objects in the photograph will stand out in even sharper relief than they would have appeared to the eye, and in this way even views of very distant

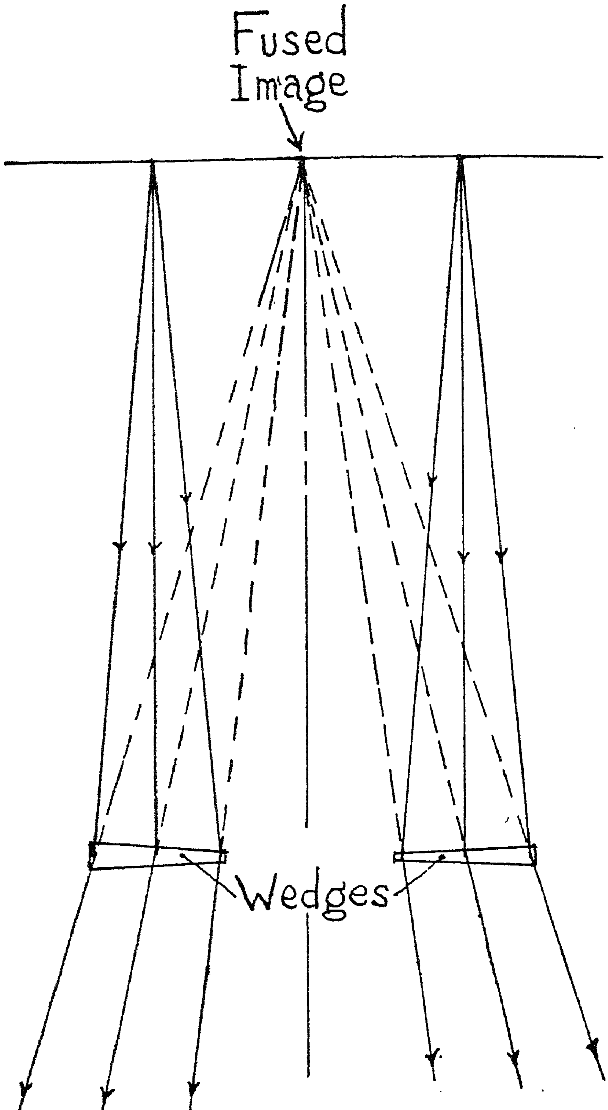


FIG. 125

Optical principle of the stereoscope

objects can be made to show stereopsis. Stereoscopic pictures have been successfully taken of the moon and some of the planets.

210. Binocular Instruments

Binocular instruments, instruments containing two eyepieces and adapted for the simultaneous use of both eyes of the user, therefore, can retain and even increase the stereoscopic power of the observer. The only requirement for this is that there be two objectives, each viewing the same object from two separated points. Separating the objectives by a distance greater than 64 mm. will *increase* the stereoscopic power. Further, any magnification of the instrument will increase the *apparent* angle of convergence, and thus also increase the stereoscopic power. It is a well-confirmed fact that the stereoscopic power of an individual is increased by training, and varies among individuals; therefore, one observer may achieve better results with a binocular instrument than another.

The binocular microscope (202) does not satisfy the conditions of two objectives. It is binocular merely to avoid the discomfort and fatigue occasioned by a monocular instrument.

211. Field Glasses

The term *field glasses* is usually reserved for those hand binocular telescopes in which the inter-objective distance is the same as the interpupillary distance of the observer. Opera glasses fall in this category.

The optical system is almost invariably that of the Galilean telescope (144) consisting of a converging objective and a diverging eyepiece, usually a simple double- or plano-concave lens, but occasionally, in better instruments, a compound lens. The result of using this type of optical system is to secure a very short telescope which is easy to hold before the eyes (fig. 126).

The Galilean system is, however, not usually very satis-

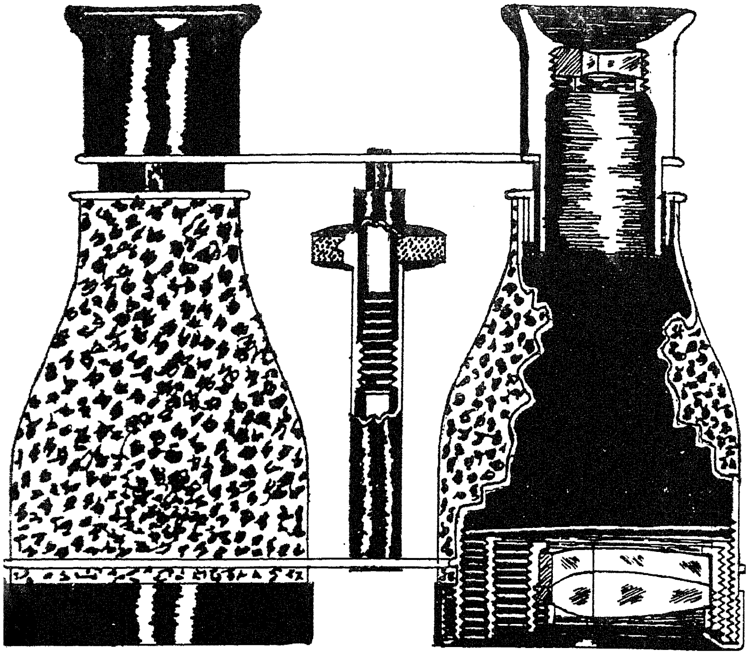


FIG. 126

Galilean type field glasses

factory, because of its necessarily small field of view. The exit pupil being virtual, the cone of rays emerging from the eye lens generally is larger than the eye can accommodate, therefore, there is likely to be a considerable loss of illumination. On the other hand, if this instrument is made with a sufficiently small exit pupil (eye lens) it is very economical of light, as there are few lenses involved, and for this reason the system is frequently used for *night* glasses.

212. Prism Binoculars

The term *binoculars* is usually reserved for binocular telescopes containing a prism erecting system which serves to

make the interobjective distance greater than the interpupillary distance, thus increasing the stereoscopic power (210).

The erecting system most frequently used is the first type of Porro system (125) in which the erecting planes of the prisms are inclined at 90° to each other; with the instrument held in a level position, these planes are at 45° to the horizontal plane containing the two optical axes, giving the greatest interobjective distance. Occasionally, binoculars using Leman prisms (126) are found, and for these the interobjective distance is even greater.

The objectives of binoculars are, of course, achromatic lenses of good quality. The eyepieces may be of any type, although the Kellner eyepiece is perhaps most frequently found. The objectives and eyepieces must, of course, be carefully matched, especially with respect to focal length (fig. 127).

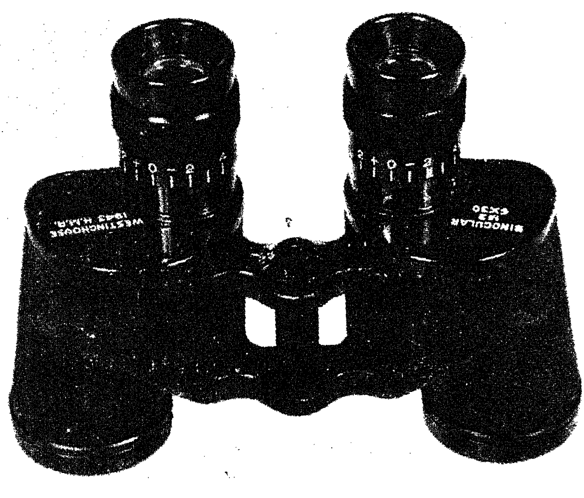


FIG. 127

A modern prism binocular

213. Interpupillary Distance and Adjustment

Since the interpupillary distance varies among different individuals, from 56 to 72 mm., binocular instruments of every type usually contain provision for changing the interpupillary distance readily. The only exception is where the exit pupils of the two telescopes are so large that the difference between these two extremes is taken up by the excessive diameter of the exit pupils. In the case of field glasses, opera glasses, and prism binoculars, the interpupillary adjustment is accomplished by mounting the two independent telescopes on a hinge. The user then merely opens or closes the instrument until the proper adjustment is attained. On better instruments, there is usually a scale on the end of the hinge, indicating the actual interpupillary distance of the setting.

In the case of field and opera glasses, using the Galilean telescope system, the exit pupil is so large that it is sometimes unnecessary to provide an interpupillary adjustment.

214. Focusing Adjustment

On many field glasses, where there is no interpupillary adjustment, the only provision for focusing is given by separately mounting and coupling the objectives and the eyepieces to shafts, the eyepiece shaft being threaded and the objective shaft containing a knurled nut. By turning this nut, the separations of objectives and eyepieces is changed to focus the instrument. Both eyepieces move together, so that there is no provision for focusing the individual eye. In better types, one of the eyepieces is focusing, as on the binocular microscope, and by this means, a difference between the two eyes of the observer (a common defect) can be compensated.

In the best prism binoculars, however, each eyepiece is mounted on an independent focusing nut, thus making it possible to focus for each eye independently.

215. Using the Binocular

In using a binocular, the first thing is to focus each telescope individually for the eyes of the user, by adjusting each eyepiece independently on its focusing nut, if this arrangement is provided on the instrument. When this is done, the side which is not being focused should be covered by the hand cupped over the objective. If both eyepieces are mounted on a shaft, the procedure is the same as in the case of a binocular microscope (202). The instrument is then pointed at the sky (or a very distant object) and the interpupillary distance adjusted until the eyes see just one round, bright field of view. The instrument is then ready for use. The common picturization of a binocular field of view as dumbbell-shaped is completely erroneous.

216. Prism Mountings

The length of the instrument is reduced (125) by the full length of the optical path through the prisms, plus twice the separation of the hypotenuse faces of the prisms (fig. 128). Thus, by merely increasing the separation of the prisms, any focal length of objective can be accommodated in an instrument whose length (exclusive of eyepiece) is approximately ⅓ the focal length.

In binoculars of long focal length (high magnification), the prisms are usually separated as shown in fig. 128a. In most binoculars, however, the arrangement is that shown in fig. 128b, where the hypotenuse faces of the prisms are almost in contact.

The prisms may be held into the body of the instrument by spring plates and screws, or may be held down to a prism plate or shelf. The prisms must be adjusted into position with great care, because any variation of the erecting planes of the prisms from perpendicular to one another will cause *tilt* or *lean* in the field of view (fig. 129). Further, any angular

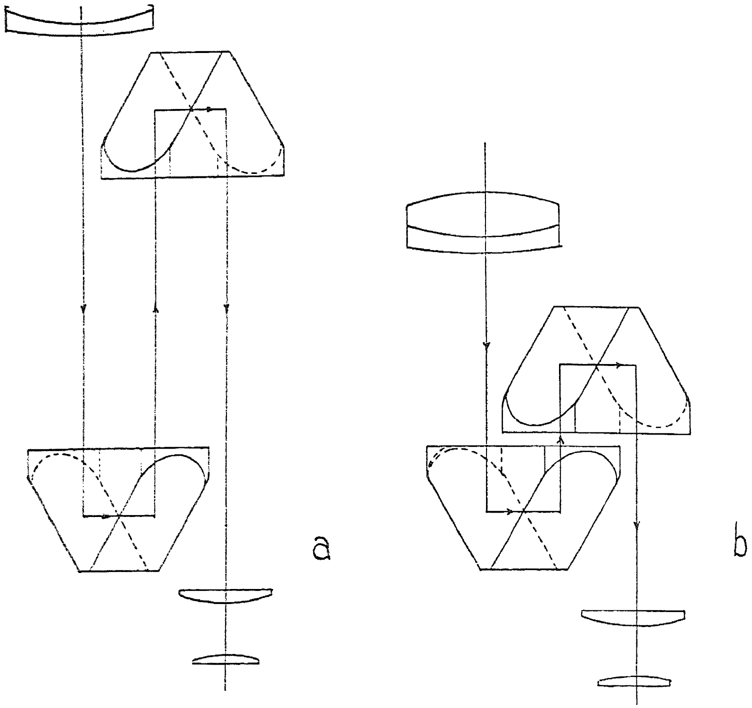


FIG. 128

Mounting of binocular prisms

deviation occasioned by the inaccuracy of the prisms themselves or by their mounting will cause a change in the direction of the optical axis of the instrument which will make it impossible to collimate (357). Prisms are matched in pairs for deviation. The usual manufacturing tolerances for the light deviation by a Porro prism is 180° ± 6′. However, many manufacturers will permit broader tolerances and then match the prisms with plus and minus errors, this way producing a perfectly good instrument, but one in which the prisms are not individually replaceable.

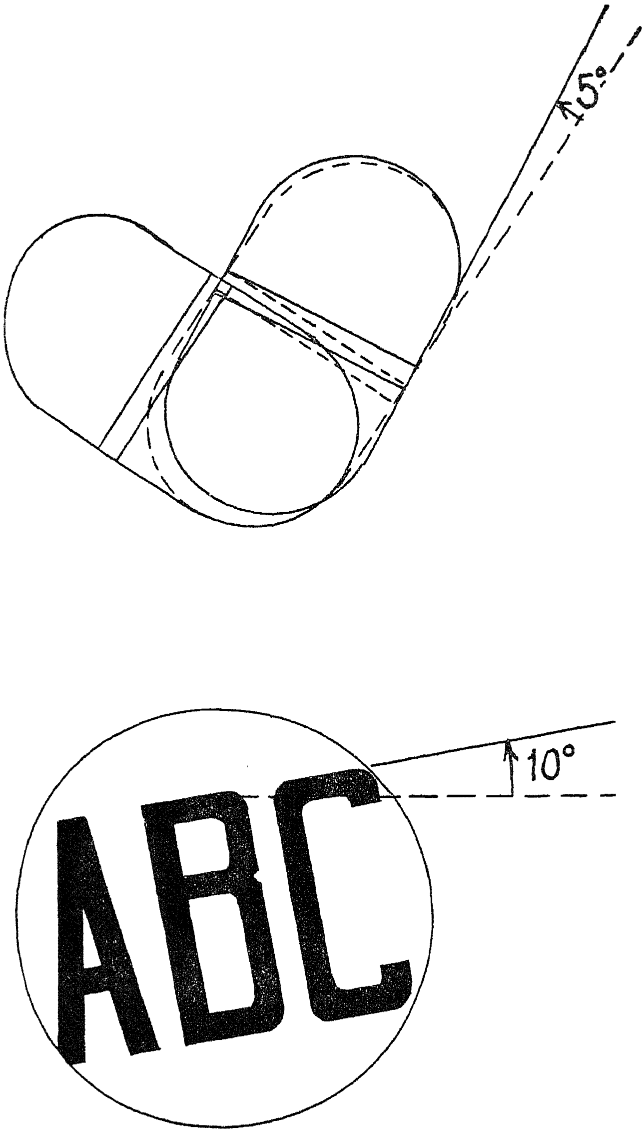


Fig. 129

Effect of maladjustment of prisms; tilt

217. Collimating and Adjustment Tolerances

It can be seen that the principal optical difficulty with binoculars is lack of parallelism of the optical axes of the two telescopes. This results in the fault known as *double vision,* in which two overlapping fields of view are seen. The eyes will automatically compensate for a considerable amount of double vision, and the defect may not be noticeable when using the instrument, but its presence will cause severe eyestrain if the instrument is used for an extended period. The lack of parallelism of the optical axes permitted by most manufacturers is 3′ of arc in a vertical direction, 3′ convergence or ½′ divergence in a horizontal direction. The procedure of paralleling the optical axes is known as *collimation* (chapter XXIX). The eyes converge more readily than they diverge, hence the difference in the tolerances in the horizontal direction.

There must also be parallelism between the optical axes of the two telescopes and the axis of the hinge, in order that the optical axes may be parallel for all interpupillary settings. The tolerance here is much broader, however, since the full range of interpupillary adjustment is accomplished by only a small arc of the hinge rotation.

The procedure for collimation will be outlined in chapter XXIX. Instruments vary in the methods provided for collimation. In some cases, adjusting screws on the prisms are used; in others, the objectives are mounted in eccentric cells.

218. Types and Designations, Optical Characteristics

The common method of designating binoculars is to state the magnifying power and the diameter of the objective in millimeters. For example, 6X30 means magnification 6X, diameter of objectives 30 mm. The usual types to be found are 6X30, 6X40, 7X35, 7X50, 8X50, 10X50.

If we assume the entrance pupil to be the objective cell (which is never exactly the case, but usually quite nearly so)

the exit-pupil diameter in millimeters will be given by dividing the first number of the designation into the second. This is usually about 5 mm., the normal opening of the pupil of the eye in medium bright illumination.

In the case of night glasses, we can assume a somewhat larger pupillary opening, and thus night glasses, designed to take the fullest possible advantage of what light is available, may be made with an exit pupil up to 7 mm. in diameter, note the 6X40 designation listed above.

The Galilean type field glass is sometimes preferred for night observation, because of the reduction in light absorption due to the absence of the erecting system, but it must be so designed as to have exit pupils of the optimum size.

Hand binoculars are infrequently found giving a magnification greater than 8X, since it is extremely difficult to hold even an 8X glass steadily enough to observe clearly. 12X and 16X binoculars are manufactured, but they are usually used with tripods.

CHAPTER XXI

Projectors

219. Purpose and Uses

A projector is an optical instrument designed to form upon a screen an enlarged real image of a given object. Projectors are used for a variety of purposes, for projecting lantern slides, films, and motion pictures, for making enlargements of photographic negatives, in contour projectors, for forming an enlarged image of the profile of a gear tooth, for projecting enlarged images of opaque objects, etc. Some are simple, some elaborate.

220. Optical System

The projecting system consists of nothing more than a projection lens, usually a pair of achromatic lenses separated by a considerable interval. In this way, a projecting lens is similar in arrangement and function to a lens erecting system or a camera lens.

The projection lens must be especially corrected for curvature of field and distortion. If colored objects are to be projected, a high degree of achromatism in the projection lens is necessary. Since the projected image is usually quite large with respect to the object, aberrations will be especially noticeable, and good projectors must be highly corrected.

The better projectors have condensers to illuminate the object evenly and intensely. The condenser, like that of a microscope, must be so adjusted as to give even illumination over the entire area of the object, and must not form an image of the source, such as a filament, in the plane of the object.

The important parts of a projector are the *projection lens;* the *object holder* or mechanism; the *condenser*; and the *illuminator.*

The projection lens (see fig. 130) is usually composed of two achromatic doublets, with a diaphragm between, and the design is similar in principle to that of a camera lens, in that the aberrations of one component are balanced against equal aberrations of opposite sign in the other. Focusing is usually provided for by a rack and pinion moving either the entire lens or the front component.

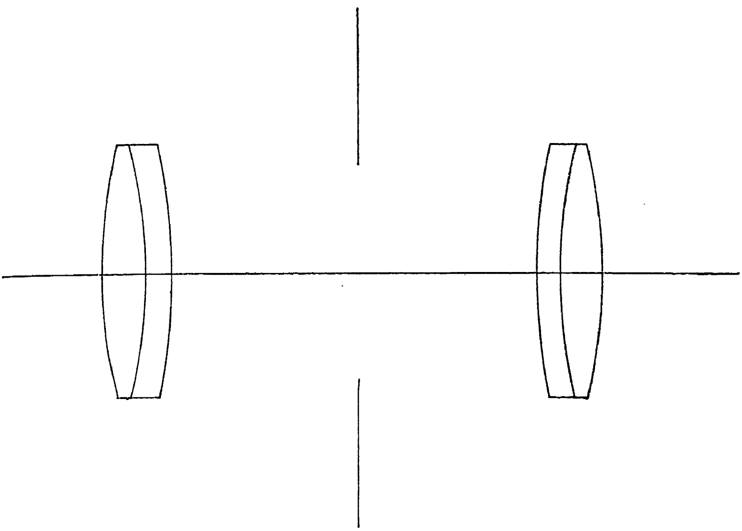


FIG. 130

The projection lens

222. The Condenser

The purpose of the condenser is to pass light through the object in such a direction that it will pass through the projection lens. This is usually done by focusing an image of the source

upon the entrance pupil of the projection lens. The object is held as close to the condenser as possible, so the condenser must usually be of considerable diameter. It generally consists of two plano-convex lenses arranged with the plane sides outward, as in the Ramsden eyepiece (133, fig. 131). This permits good corrections, as we saw in chapter XV.

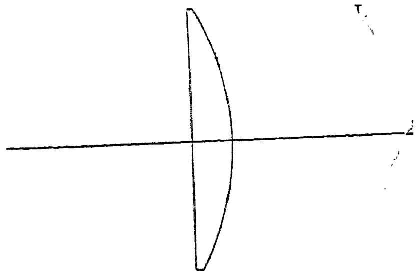


FIG. 131

A simple condenser for a projector

223. Illumination

The positive crater of a carbon arc is about as brilliant a source of light as can be secured, but has the disadvantage of being small in size. Illumination by electric lamp is more common, the lamp filaments being usually arranged in a square pattern of parallel coils. A concave mirror placed behind the source with its principal focus half way between itself and the source forms an image upon the source itself and more than doubles the intensity of the illumination.

Projectors usually require very great illumination, using from 250W to 1000W lamps. These lamps become very hot after a few minutes' operation, and the lamp chamber of a projector must, therefore, contain provision for cooling, usually by means of a fan.

224. Motion Picture Projectors

It has already been stated (179) that the motion picture projector forms a greatly enlarged image of the scenes recorded

upon a continuous strip of film. The projector feeds the film at the rate of 16 frames per second by a mechanism which permits the film to stop for a short interval while the shutter is opened and closed again. A rotating shutter is frequently found, this being merely a large disk with a sector or sectors cut out. The axis is placed so that the edge of the disk covers the projection lens, and the shutter is rotated synchronously with the film mechanism so that an open space passes in front of the projection lens 16 times each second and at just the time when the film is stationary.

The mechanism of the motion picture projector is somewhat different from that of a motion picture camera, the case of the projector requiring that the shutter remain open most of the time, the case of the camera requiring that the shutter be closed most of the time.

225. Opaque Projectors

A recent development in the field is the *opaque projector,* sometimes known as an epidiascope, which is adapted to the projection of an image such as a photograph or a printed page.

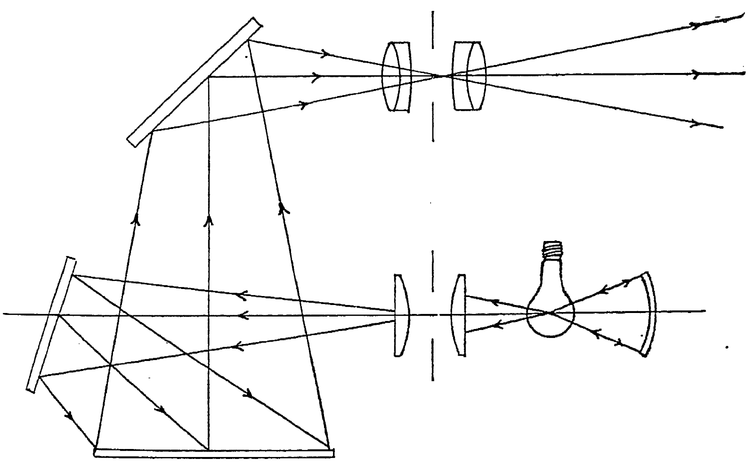


FIG. 132

Optical system of an opaque projector

These instruments are usually made so that the object may be laid on a level surface. The light from the condenser is brought onto the object by a mirror, and picked up by the projection lens after it has been reflected from a second mirror. The design of these instruments varies widely with different manufacturers, but the principle is the same (fig. 132).

The final image given by an opaque projector must be inverted in one plane, because of the effective rotation of the line of sight through 180°. If we looked at the object in the direction of the path of light through the projector, we would be seeing it from the back, and thus it would be inverted in one plane. The projection lens, like any objective, inverts in two planes, so there must be a mirror in the system to give the required inversion in one plane.

226. Self-Contained Motion Picture Unit

One type of motion picture projector used in schoolrooms, restaurants, show-windows, etc., has a screen as a part of

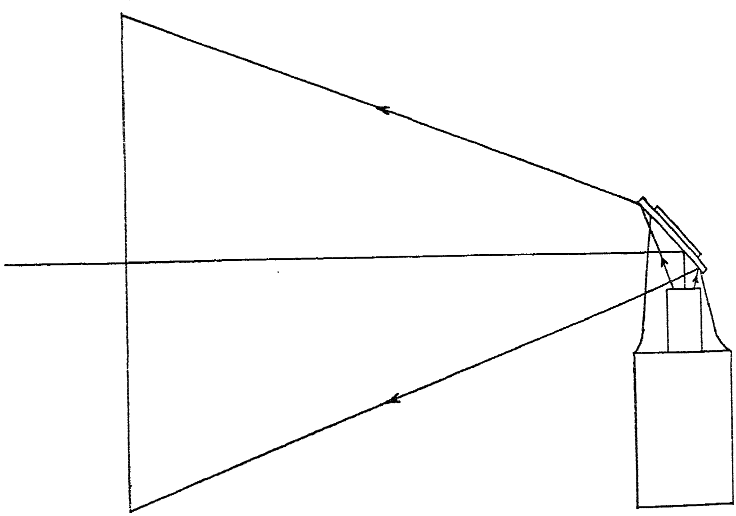


FIG. 133

Optical arrangement of the self-contained motion-picture unit

the unit, and the projection is made from behind the screen. In this case, the direction of view is reversed, and this introduces an inversion in the horizontal plane. This inversion is compensated by a mirror (or prism) placed immediately in front of the projection lens, and the projector is, therefore, set at right angles to the screen (fig. 133).

CHAPTER XXII

THE SPECTROSCOPE

227. Significance

If one were to name the invention of the most far-reaching importance in the development of modern physical science, one would be hard pressed to avoid the choice of the spectroscope. Even the telescope and the microscope, important though they are, fade into insignificance before the imposing array of physical discovery which has been made through the use of this instrument.

In chapter I we stated that this volume would not enter the realm of physical optics, but it would be gross negligence to attempt to write a book on optical instruments without treating the spectroscope, and it is necessary to discuss the wave theory of light in describing the spectroscope and its functions. Our treatment of light here, however, is not complete, and the reader is referred to any standard text on physics for a more general and comprehensive discussion.

228. History

It is ironical that the most important of modern scientific instruments should depend, in one of its forms at least, upon the one thing which the optical designer concentrates all his skill to eliminate from other instruments, chromatic aberration.

Sir Isaac Newton came so unbelievably close to the discovery of the principle of the spectroscope that one regrets that he was not responsible for it. Newton admitted the light of the sun through a pinhole into a darkened room, and allowed

the image of the sun thus formed to fall upon a screen. He then placed a prism in the beam of light in the manner shown in fig. 59, and produced a spectrum, as there described. How this took place is outlined in (104). The prism separated the different colors of light and produced a series of overlapping images of the sun on the screen which, altogether, made up the *spectrum*. Newton showed also that a second prism would combine the separated colors into white light again, moreover, that light of any one color could not be broken down further.

He proved by this that white light is made up of light of all colors, and that the breaking up of white light into its component wave-lengths was due to the dispersion of the prism, the variation of the refractive index of the glass of the prism with the wave-length of the incident light. The important fact was that the colors were present in the incident light, and were not *produced,* but merely *separated,* by the prism. If Newton had only used a slit and a lens instead of a pinhole! But it was left for Joseph Fraunhofer to make the epochal discovery that awaited the use of this simple arrangement.

229. The Fraunhofer Lines

Fraunhofer admitted sunlight through a *slit,* and, using a lens and the customary prism, formed a spectrum from the multitudinous overlapping images of the slit which were separated by the prism into a band of color. Imagine the observer's surprise when he saw the spectrum crossed by many dark lines, some faint, some very prominent. It could mean only one thing, certain images of the slit were absent, that is, certain wave-lengths were absent from the incident light (fig. 134). In Newton's experiment, the images were circular, and overlapped to such an extent that the missing images were not evident.

Fraunhofer discovered that the locations of these dark lines in the spectrum never varied, that certain specific wave-lengths

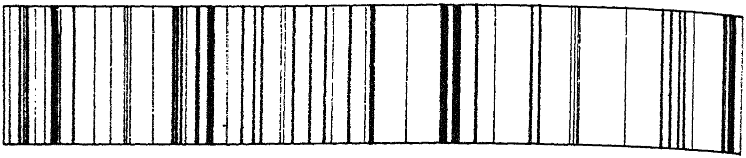


FIG. 134

Absorption (dark-line) spectrum showing Fraunhofer lines

were permanently and conspicuously absent from the sun's light; and he gave them indicatory letters. These letters, together with the name Fraunhofer, are still in use today, although modern instruments have brought to light many thousands of dark lines in the spectrum of the sun, rather than the few which Fraunhofer was able to observe with his simple equipment.

230. Bright-Line Spectra

It is obvious that this discovery would lead Fraunhofer and others to many other experiments upon the effect of prisms on light. Light from other sources, such as candle flames and the incandescent vapors of all substances which could be made to produce incandescent vapors, was studied.

It was found that when a substance was heated to incandescence, its light passed through a prism and its spectrum produced, it was usually not like the spectrum of the sun, it did not consist of a continuous sequence of colors crossed by dark lines. The dark lines were conspicuously absent from spectra produced by any laboratory source, and although sometimes substances gave a *continuous spectrum,* more frequently the result was a series of *bright* lines of different colors with dark areas between. In other words, the light from these laboratory sources consisted of a collection of a few very specific wave-lengths and no others at all (fig. 135).

It was not long before it was discovered that the pattern

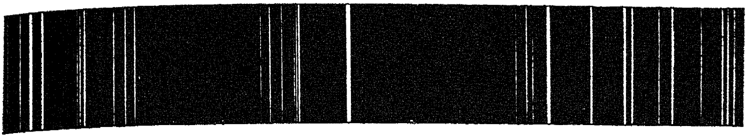


FIG. 135

Emission (bright-line) spectrum

of lines (slit images) given by a particular substance was *characteristic of the substance producing it,* since the pattern of a given substance never varied and was never duplicated by any other substance. The substances which could thus be identified were chemical *elements*. Chemical *compounds* usually broke up into their constitutent elements under the heat of incandescence, and a compound would show the line pattern of each of the constituent elements superimposed in one bright-line spectrum.

231. The Laws of Bunsen and Kirchhoff

We need not dwell on the details of the various explanations which were offered for the existence of spectral lines, but can go directly to those laws of spectra which were subsequently proven to be complete and correct; namely, the three laws of Bunsen and Kirchhoff:

1. Any solid, liquid or gas under pressure will, if heated to incandescence, give a *continuous spectrum,* will give off white light, light in which *all* wave-lengths are present in greater or lesser abundance.
2. Any substance in the form of a gas, under very low pressure, will give off a *characteristic bright-line spectrum;* will give off light of only certain specific wave-lengths, each of which is peculiar to the radiating substance.
3. If white light is allowed to pass through a thick layer of low-pressure gas, which is at a lower temperature than that of the substance giving the white light, then the result

will be a continuous spectrum upon which is superimposed a *dark-line spectrum,* in which the dark lines are in the same positions as would have been occupied by the bright lines of the low-pressure relatively cool gas. This means that a gas at low pressure is capable of *absorbing* just those specific wave-lengths of light it is capable of emitting, and can extract these from an incident beam of white light.

At last an explanation of the Fraunhofer lines was available. The light from the intensely hot, but dense, interior of the sun, representing a continuous spectrum, passed through the cooler and rarer gases in the sun's atmosphere, and these relatively cool gases extracted from this radiation just those wave-lengths of light which they were capable of emitting. Of course, these atmospheric gases were hot, too, but not nearly so hot as the sun's interior.

Naturally, the laws of Bunsen and Kirchhoff were not originally formulated in the words given above; we have taken the liberty of including the significance which was subsequently disclosed.

232. The Origin of Spectra

The story of how the explanation of spectra led to the epic discoveries represented in the modern view of the nature of matter (it gave the clues necessary to the successful investigation of the structure of the atom and subsequently to modern atomic theory, and eventually led to the complete overthrow of the previously held concepts of the nature of scientific laws and of the universe) is a fascinating one, but it is too long and we have no space for it here. Neither has it anything to do with optical instruments.

233. The Spectroscope

The important fact which emerges from the previous discussion is that every chemical element has a characteristic spectrum, bright- or dark-line, *emission* or *absorption,* re-

spectively. Therefore, by analysis of the light from an unknown substance, the spectroscopist can determine exactly what substances are present. The spectroscope is exceedingly sensitive in this respect, quantities of an element far smaller than can be detected by any other method of analysis can be readily detected by spectroscopy. The spectroscope is by far the most sensitive of all instruments of qualitative analysis. Further, fairly reliable estimates of quantities of various substances present may be made by study of the *relative brightnesses* of spectral lines.

Probably the most important use of the spectroscope in modern science is in the study of the stars. A famous philosopher once remarked that "there are some things in nature which we shall never know, such as the internal constitution of the stars." Today, thanks to the spectroscope, we know the constitution of the stars, or at least of their atmospheres, better than we know perhaps anything else about them. Further, the astrophysicist, from a study of his spectra, can determine constitution, temperature, pressure, velocity, mass, density, and many other salient facts about the stars.

234. Direct-Vision Spectroscope

The simplest type of spectroscope is the *direct-vision spectroscope* (fig. 136). In its most elementary form, it con-

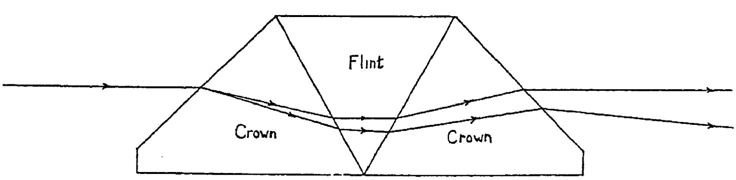


FIG. 136

Optical system of the direct vision spectroscope

sists merely of a slit and a series of prisms so arranged that the combination gives dispersion but no deviation. Three

prisms are usually the minimum necessary, but five are more common. The prisms are made of two different types of glass, there being two flint and three crown prisms in the five-prism type. The crown elements have a larger refracting angle than the flint elements, and, of course, the flint glass has a much higher dispersion.

The direct-vision spectroscope is frequently equipped with a collimating lens in front of the prism combination. This furnishes parallel light to the prisms and permits utilization of the entire area of the prism. The eye is held close to the rear prism and a series of slit images are seen (formed by the eye), constituting a spectrum. In such an instrument, of course, the lines are not very widely spaced, and it is useful only for crude qualitative work. Sometimes a reference scale is arranged so as to be seen reflected in the surface of the rear prism.

235. The Prism Spectroscope

The modern prism spectroscope (fig. 137) consists of four essential parts: a *slit,* usually adjustable in width, a *collimator,* a *prism,* and a *telescope.*

The slit is the most difficult part to construct. Its blades must have accurately ground and polished edges, and the two sides must be parallel within about .0001″. In order to achieve the greatest possible resolution, the slit images must be very narrow, which means that the slit itself must be very narrow. in better instruments, both blades of the slit are adjustable, so that the center of the slit image does not change position in the field of view when the width of the slit is adjusted, facilitating the placing of the cross hairs. In cheaper instruments, only one blade is adjustable, which requires that the cross hairs of the telescope be focused on the edge of the image.

The collimator consists merely of a lens with the slit at its principal focus. It produces parallel light for passage through the prism. The larger the diameter of the collimator, the more

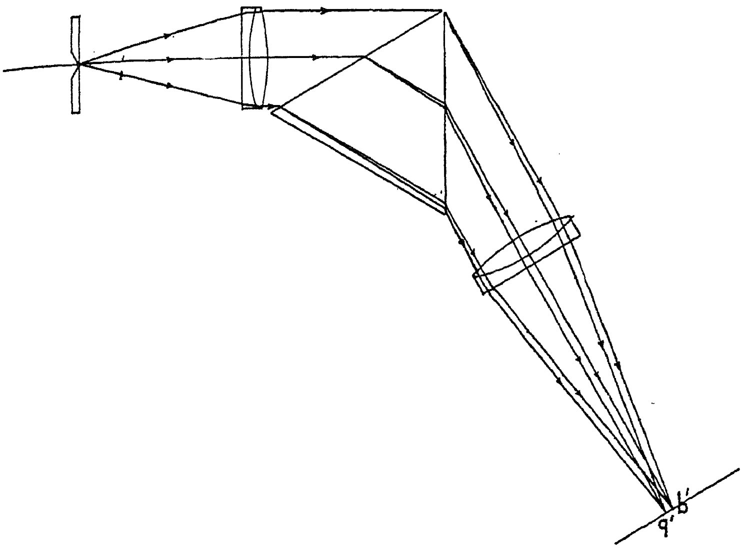


FIG. 137

Optical system of the prism spectroscope

light will be available in the spectrum, but it must be remembered that if the prism is not sufficiently wide to take in all the light from the collimator, light will be lost around the edges of the prism.

The prism itself is large and thick, and of such a vertex angle that the light will be well dispersed but not internally reflected. A 60° prism is almost invariably used. It is usually made of glass of as high a dispersion as possible, for obvious reasons, which means a dense flint glass.

A view telescope receives the parallel bundles of light emerging from the prism and forms the images of the slit in the focal plane of its eyepiece. Ramsden eyepieces are usually used. Quite obviously, the lenses used in collimator and view telescope must be well corrected, especially for chromatic aberration.

236. The Analysis of Wave-Length

It may be seen that a spectroscope is simply an instrument for analyzing light according to wave-length. Since the position of a given slit image is determined by the direction the light comprising it had when it entered the view telescope, and since this direction is determined by its wave-length and the deviation of the prism, we can develop means of measuring the wave-length accurately.

The prism can most effectively be used when the angle of incidence at the incident face is the angle for minimum deviation* (39), and this position is readily determined precisely (242), and for a 60° prism this requires that:

$$\sin i_o = \frac{n}{2}$$

where i_o is the angle of incidence (and emergence) and n is the index of refraction of the prism. This varies with the wave-length, of course, so the angle between the collimator and prism must be set for some selected wave-length. In the examination of a complete spectrum, the prism is usually set for the D-line of sodium (Fraunhofer nomenclature) at 5896 Å, in the yellow region of the spectrum. This is the index of refraction given in tables of optical glass (107). The prism mounting is usually adjustable to make this positioning accurately.

From equation (5), the amount of deviation for this special case is:

$$D'_o = 2i_o - 60°$$

and, if we let dn be the change in index of refraction due to

*The reason for this lies in the astigmatism and distortion produced by a prism in which the light is deviated by refraction, these being a minimum when the deviation is a minimum.

a change in wave-length from $\lambda = 5896$ Å to $\lambda = \lambda_1$, and dD be the corresponding change in the deviation, then:

$$dD = \frac{4dn}{\sqrt{4 - n^2}}$$

It will be noted that this becomes imaginary for n greater than 2, which is easily understood when we remember (38) that for n greater than 2, a 60° prism becomes totally reflecting for all incident light.

Now the distance, ds, in the image plane, from the center of the field to the image point q′ (fig. 137), where f is the focal length of the objective is (if θ is small):

$$m'q' = f\theta$$

But, $\theta = dD$, so:

$$m'q' = ds = \frac{4fdn}{\sqrt{4 - n^2}} \qquad (39)$$

This distance may be measured by a suitable reticle, and the wave-length of a given spectral line thus established, if we know the index of refraction of the prism for all wave-lengths (243).

237. The Spectrometer

A spectroscope which is furnished with a graduated rotating table for the telescope and another for the prism, for measuring angles of deviation, is known as a *spectrometer*. The telescope is mounted on a rotating arm, with its axis of rotation in the center of the prism table. Vernier scales (264) are usually provided at two points on this ring, 180° apart, because, by such an arrangement, errors in alignment of rotating axis and scale are compensated by averaging the two readings from opposite sides of the table. The prism table also rotates, with a scale and verniers, and both the prism table and the telescope

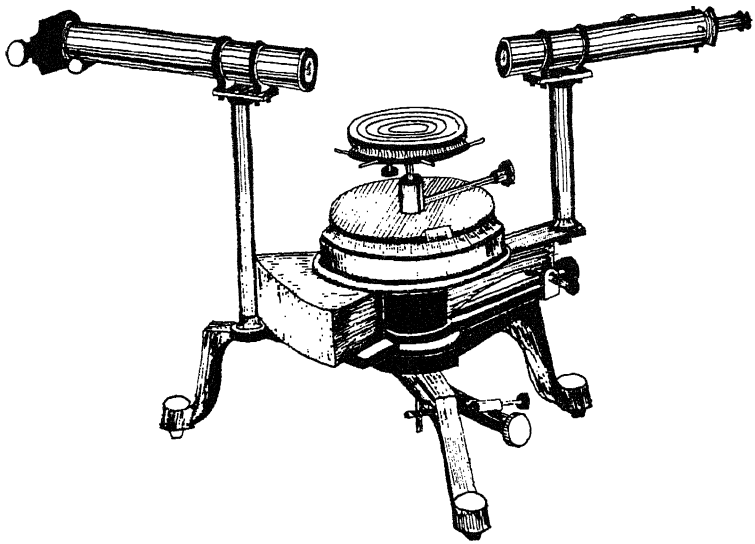


FIG. 138

The spectrometer

table are provided with adjusting screws for accurate leveling with respect to the axis of rotation. The telescope contains a reticle, usually simple cross hairs. The use of the spectrometer in measuring angles is discussed in (242, fig. 138).

The spectrometer, of course, is only a somewhat more elaborate spectroscope, and any operation which can be performed with the spectroscope can be performed with the spectrometer.

238. The Abbé Auto-Collimating Spectrometer

This instrument eliminates the necessity of a collimator and facilitates adjustment. The slit is mounted in the focal plane of the eyepiece (fig. 139), occupying one half of the field of view, and is illuminated from the side by means of a right angle prism. The telescope objective acts as collimator, sending out parallel light. This parallel light is reflected back into

the instrument and the resulting image of the slit is brought into coincidence with the actual slit by rotating the test object on its table. In measuring the refractive index of a prism, the prism is so adjusted that the refracted ray into the prism meets the rear face perpendicularly, in which case the portion which is reflected at this surface will return over its original path. In measuring angles of prisms, each face is adjusted in turn so that it is perpendicular to the optical axis of the telescope.

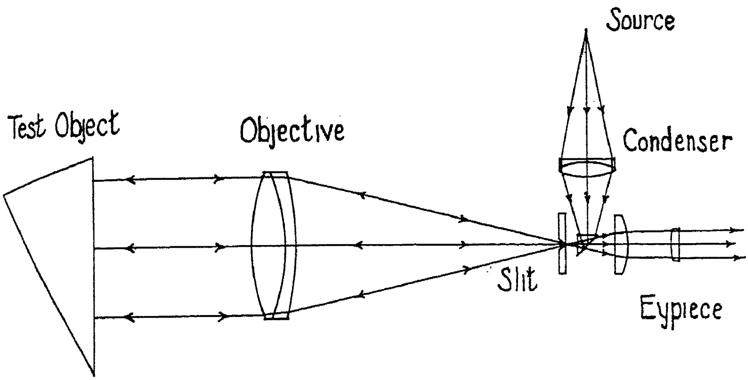


FIG. 139

Optical system of the Abbé auto-collimating spectrometer

This instrument does not produce a spectrum, and it operates with *monochromatic* light.

239. The Constant-Deviation Spectrometer

The spectrometer is often constructed in the *constant deviation* form, of which there are two types. The first type makes use of a special *constant deviation* prism (fig. 140) which, although usually constructed of one piece of glass, can be thought of as representing three prisms, two 30° and one 45°. This prism gives a constant deviation of 90° for any wave-length, the angle of incidence necessary for a 90° deviation being different for different wave-lengths. The position of the prism

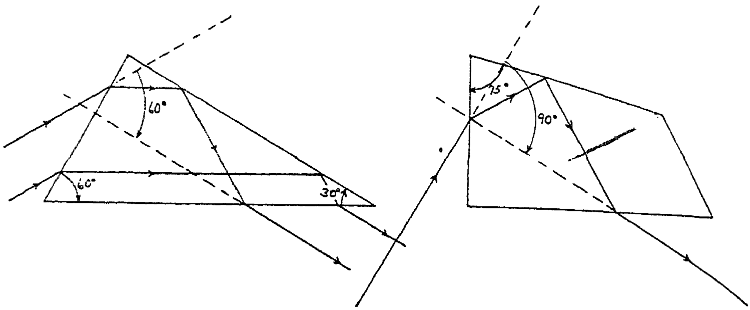


FIG. 140

Constant deviation prisms

is adjusted by rotating its table until the subject wave-length is brought against the cross hairs of the reticle and a scale reading is taken. Many spectroscopes of this type have scales reading directly in wave-length.

The second type of constant-deviation spectrometer consists of a prism and mirror combination, the mirror being placed

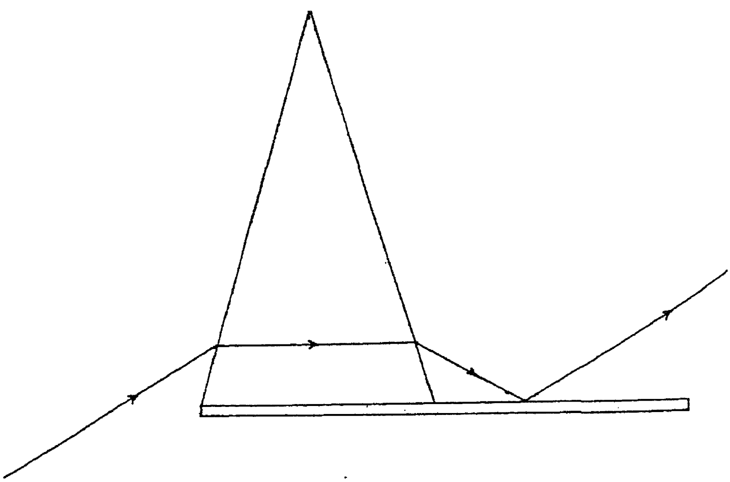


FIG. 141

Special mounting of quartz prism for constant deviation

parallel to the base of the prism (fig. 141). A moment's study will assure the reader that the ray will leave the mirror parallel to its original path of incidence into the prism. Measurements are taken in the same way as with the first type. The second type is frequently used for the measurement of wave-lengths in the infrared (252).

240. Reticles and Reference Scales

In the spectrometer, the reticle usually consists of cross hairs in the focal plane of the view telescope eyepiece. In a plain

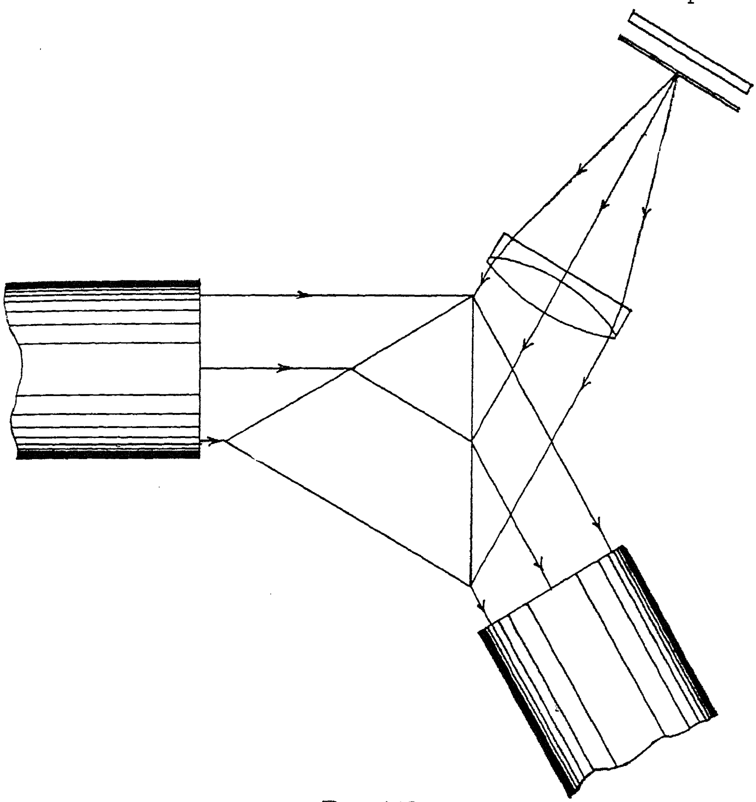


FIG. 142

Method of superimposing a reticle scale

spectroscope, a most usual arrangement is that shown in fig. 142. A third optical system is added to the instrument, consisting of a suitable scale, usually in arbitrary units, illuminated through a ground-glass window and located at the principal focus of a lens. The light from this scale is rendered parallel by the lens, and is reflected from the emergent face of the prism in such a way as to enter the objective of the view telescope and be imaged simultaneously with the spectrum.

When such an arrangement is used, the view telescope may be mounted so as to rotate through a small arc about the prism as a center, and thus bring into view portions of the spectrum and the scale which might otherwise be outside the field of view of the telescope. If the prism were rotated, the position of the scale with respect to the spectrum would change.

Another method of superimposing a scale on the spectrum is illustrated in fig. 143. Here the scale collimator is attached to the telescope, and the image of the scale is presented to the objective by means of a thin plane-parallel glass plate placed

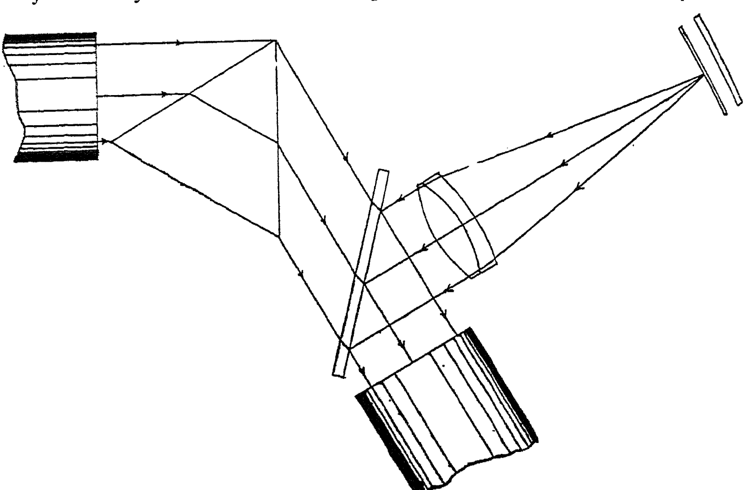


FIG. 143

Alternative method of superimposing a reticle scale

at an angle of 45° to the optical axis of the telescope. Such an arrangement as this is necessary in the grating spectroscope (245). The spectrometer, however, whether or not such an arrangement is provided, must have a reticle in its telescope.

241. Illuminating the Slit

Since the width of a spectroscope slit is not very great (0.1 to 0.001 mm.), one of the principal difficulties in using a spectroscope or a spectrometer is to obtain a sufficient concentration of light on the slit. This is usually accomplished by focusing an image of the light source upon the slit with a suitable lens. Such a lens should be of fairly short focal length and large aperture, to make the image upon the slit as small as possible (but not too small to give a reasonable length of line in the spectrum) and admit a large quantity of light.

242. Focusing and Operation of the Spectrometer

The spectrometer is used for three principal purposes: 1. To measure the angular deviation of light of known wave-length to determine the index of refraction of a sample prism; 2. to measure the angular deviation of light of unknown wave-length to determine its wave-length (the index of refraction of the prism being known); 3. to measure the refracting angle of a sample prism.

In any case it is necessary first to focus and collimate the instrument. The telescope is focused on a distant object (preferably a star), adjusting the eyepiece and objective or reticle until clear definition of the object is attained and parallax (367) is removed. In many spectrometers, the telescope is removable from the base in order to make this adjustment. The telescope is then placed on the base and swung about until it is facing directly the collimator. The slit is then adjusted with respect to the collimator lens until a sharply defined image of the slit is seen in the telescope. The prism is removed for this adjustment. The instrument is now ready to make a measurement.

1. To measure the angular deviation of light, the telescope is rotated on its turntable until an image of the slit is seen against the vertical cross hair of the reticle. No prism is present during this adjustment. The scale reading on the turntable is taken. The prism is placed on its table, and the telescope swung into an approximate position to receive the refracted light. By moving the prism and the telescope the slit image is brought into the field of view. The prism is rotated in the direction of a *decreased* angle of deviation, bringing the telescope up each time the image passes outside the field of view. (Remember at this stage that the telescope of a spectrometer is an *inverting* telescope, therefore, the movement in the field of view is opposite to the actual movement of the light.) When the direction of movement of the image *reverses* (changes to an increase), the position of minimum deviation has been reached; the telescope is adjusted carefully until the vertical cross hair cuts the slit image and a reading of the turntable scale is taken. The difference between the two readings of the turntable scale is the deviation, and the index of refraction can be computed from a known wave-length, or the wave-length from a known refractive index.

2. When the spectrometer is used to measure the index of refraction of an unknown medium, it is necessary that the slit should be supplied with monochromatic light; light of a known and specific wave-length. There are many substances which give spectral lines whose wave-length is accurately known.

3. Since the actual refracting angle of a prism of sample material is seldom known very accurately, it is usually necessary, after making the measurement described above, to measure this angle in order to apply the equation for the determination of the index of refraction. This is done in the following manner:

The prism is placed with its vertex pointed toward the collimator. In this position, the two refracting faces of the prism split the beam of light from the collimator into two parts, as

shown in fig. 144. The telescope is then swung into position to form images of the slit from each of these two beams successively. The difference in the readings of the turntable scale for these two positions is twice the refracting angle of the prism, as may be seen from a little study of the diagram.

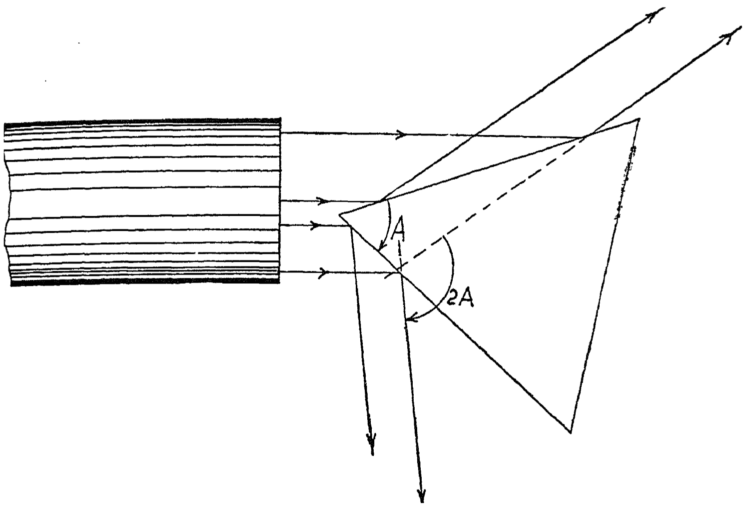


FIG. 144

Position of prism for measuring refracting angle

The above procedures have been described with reference to the ordinary type of spectrometer. In the case of the auto-collimating or the constant-deviation types, other methods are used, which are indicated in the description of the respective instruments.

243. Calibration

Since the refractive indices of a given material prism will vary within small but not insignificant limits from prism to prism, it is necessary, in order to make actual measurements of wave-length, to provide a *calibration curve* for the particular

prism used in an instrument. This is done by making measurements of the deviation of a number of standard wave-lengths, calculating the index of refraction for each of these, and then drawing a smooth curve through the values thus obtained. This curve may be used to give the index of refraction or the deviation corresponding to any given wave-length. This curve is only approximately accurate, however, and it is impossible to make a really accurate original measurement of wave-length with a prism spectrometer. The grating spectrometer, which is used for this purpose, is described in (245).

244. The Diffraction Grating

The prism spectroscope is not the most effective type of spectroscope, and we shall, therefore, proceed to a discussion of the grating spectroscope. This instrument depends upon a phenomenon of light known as *diffraction,* an effect not commonly observed but easy to demonstrate under the proper conditions.

The existence of diffraction is a proof of the wave character of light. It depends upon two characteristics of wave motion: 1. that, whenever a wave front strikes a surface, it sets up a *new set of point sources;* 2. that the concentric wave structures surrounding each of the point sources combine to produce a new wave front. How this occurs is described in the proof of the law of reflection (appendix I). In a case of reflection or refraction, the new point sources set up at the surface constitute *all* the points of the surface, and the form of the new combined wave front will depend upon the form of the incident wave front and the form of the surface, and there will be only *one* resultant wave front. In the case of diffraction, the situation is somewhat different.

The *diffraction grating* represents an *interrupted* surface, producing point sources, obtained by ruling a large number of accurately straight and parallel scratches on a suitable surface, for example, clear polished glass. The scratches represent

opaque regions, the clear spaces between are narrow slots through which light can be transmitted.

As shown in fig. 145, each slot in the grating may be considered a separate source of concentric waves. But, in this case, if we draw tangents to these sets of waves, we find a

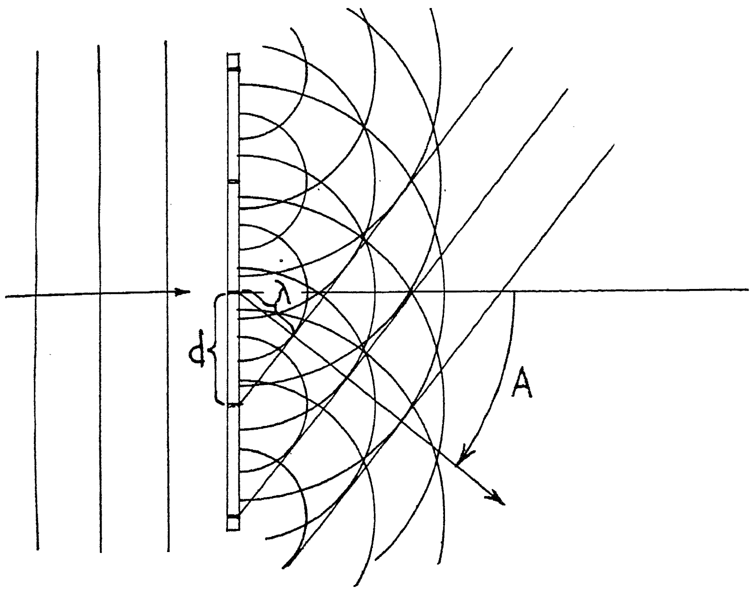


FIG. 145

Diffraction by a grating

number of different possible positions for them. From the figure, the relation of these evidently becomes:

$$\sin A = \frac{m\lambda}{d} \tag{40}$$

where λ is the wave-length, d the separation of the slots, and A the angle between the normal to the grating and the direction of the new wave front; m may take on any integral value, including 0.

The effect of a diffraction grating is, therefore, to split up a parallel beam of incident light into a number of separate parallel beams, leaving the grating in different directions. There is, of course, a beam perpendicular to the grating, corresponding to $m = 0$. This is the *normal beam.* The beam nearest to the normal beam, corresponding to $m = 1$, is called the *first-order beam,* the next, corresponding to $m = 2$, the *second-order beam,* etc.

It is clear that the separation of the different beams will be greater the smaller d becomes, and that for any reasonably large separation, d must be of the same order of smallness as λ, the wave-length of the light. Since λ is of the order of 1/50,000," diffraction gratings must be ruled as closely as 15,000–30,000 lines per inch.

The significant fact for our purposes is that A is a function of the wave-length, which shows that not only will there be a division of the incident light into different orders but that there will be a separation *by color* in each order. This means that if a lens is interposed in any of the resultant beams, it will produce a *spectrum* in its focal plane.

245. The Grating Spectroscope

The grating, therefore, may be used in place of the prism in a spectroscope, and no change in the optical system of collimator or telescope is necessary. The collimator and the slit serve to furnish a parallel beam of light to the grating, and the view telescope is adjusted to lie in the path of any one of the resultant beams (fig. 146).

246. Relative Advantages of Prism and Grating

For most purposes, a diffraction grating is far superior to a prism as a producer of spectra. In the first place, the dispersion of a grating is much greater than that of a prism, the different lines, or wave-lengths, being spread much farther

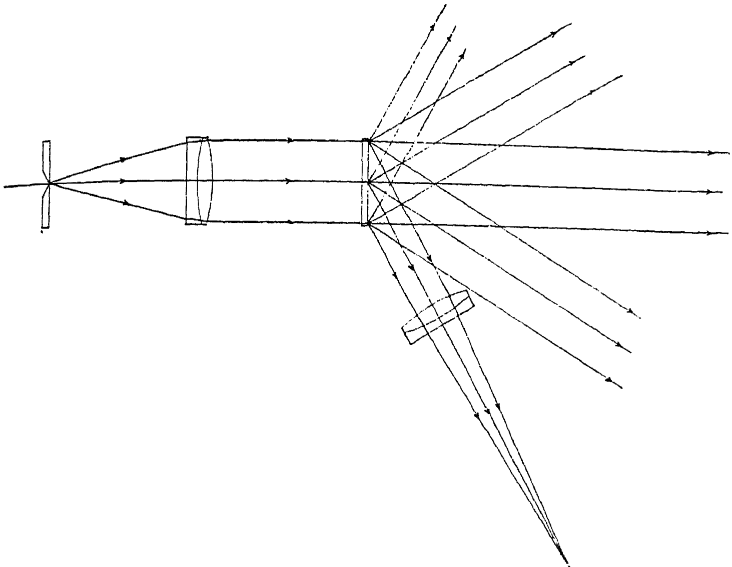


FIG. 146

Optical system of the grating spectroscope

apart. This, of course, greatly facilitates observation. Secondly, there is a definite and simple geometrical relation between the position of the spectral line and its corresponding wave-length, whereas in the case of a prism, its determination depends upon empirically determined properties of the material comprising the prism. This makes it possible to make a direct determination of absolute wave-length with a grating spectrometer, a procedure which, it was pointed out, was not possible with the prism instrument.

Another advantage of the grating is that the sine of its deviation is proportional to the wave-length, which means that the spectrum is approximately *normal.* In the case of a prism, the dispersion is many times greater in the blue than in the red It should be noted that the spectrum produced by a grat-

ing is reversed with respect to that produced by a prism, the deviation being greater for the red light with a grating, while the opposite is true for a prism.

A diffraction grating is, of course, much more expensive than a prism, but this is no particular drawback in the case of precise scientific instruments. Its most serious drawback is that it is extremely wasteful of light. A large proportion of the incident beam is contained in the *undispersed* normal beam. There is a complete series of spectra on each side of the normal

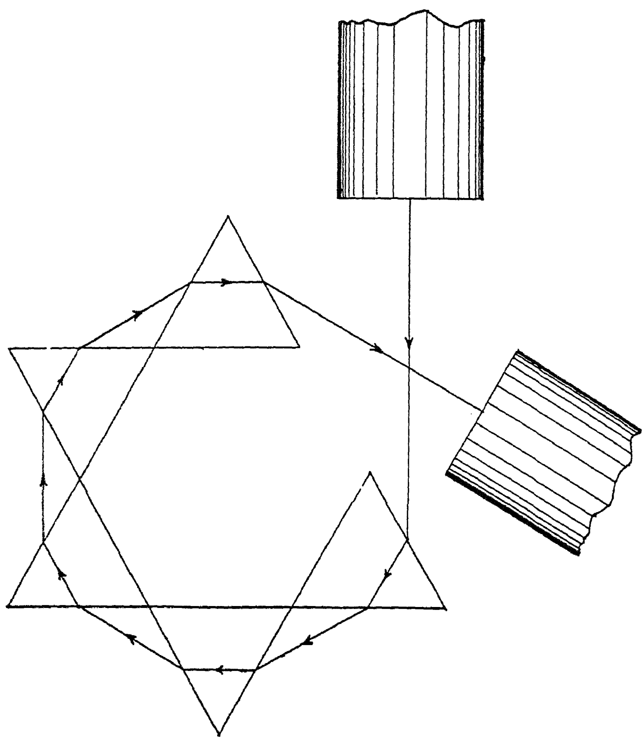


FIG. 147

Spectroscope with train of prisms

beam and, while these rapidly decrease in brightness as the order advances, the amount of illumination to be found in

one first-order spectrum (usually the first order is the one chosen for examination because it is the brightest) is only a fraction of the whole. This disadvantage is especially noticeable in astronomical spectroscopy, where it is impossible to apply the grating to any but the brightest stars due to lack of sufficient light, even with the largest telescopes.

In recent years, however, it has been found possible to produce special gratings with certain line contours, which give a much greater than normal concentration of light in one of the beams. These gratings have been extremely useful in work where illumination is critical.

It is possible to equal the dispersion of a grating by using a train of prisms, as shown in fig. 147, but the light absorption in the prisms then becomes comparable to the light loss in a grating.

247. The Measurement of Wave-Length

In the case of the grating spectrometer, the angle A in equation (40) replaces the D for the prism, and we have, for the first-order spectrum:

$$ds = \frac{fd\lambda}{g} \tag{41}$$

where ds is the displacement in the field of view of a small increment of wave-length, $d\lambda$, from a standard in the spectrum being observed, f is the focal length of the telescope objective, and g the grating constant or space between the rulings.

248. The Concave Grating

In many modern spectroscopes, the transmission grating described is replaced by the reflection grating, in which the grating is ruled on a reflecting surface, speculum metal or a metallic deposit on glass. This has the advantage of making it possible to eliminate glass from the instrument entirely (except for

eyepieces, usually replaced by photographic plates) by the use of a *concave* reflecting surface.

In the concave grating described first by Rowland, the source and the various spectra all lie on the circumference of a circle whose diameter is equal to the radius of curvature of the grating. The spectra thus produced are very nearly normal; the dispersion being almost the same throughout the spectrum. Nearly all modern grating spectroscopes of high dispersion are constructed on this principle (fig. 148).

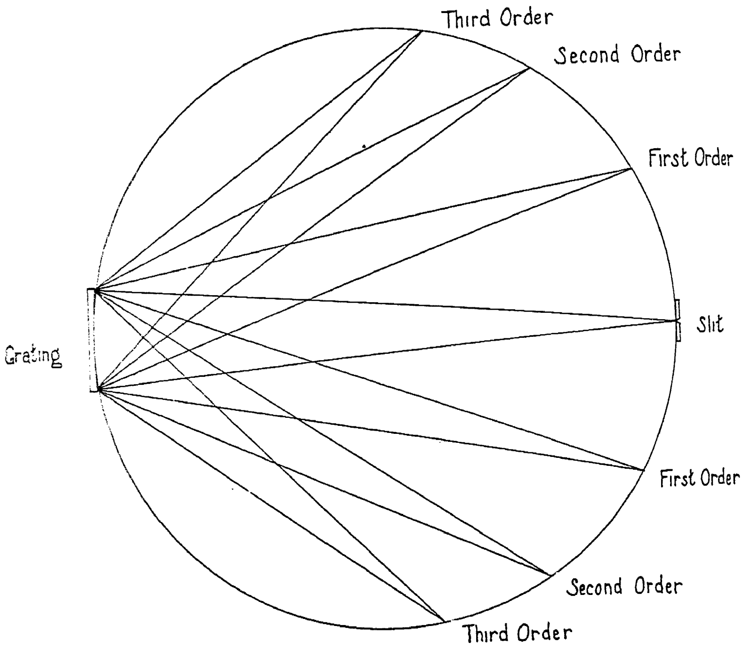


FIG. 148

Rowland mounting for concave grating

249. The Spectrograph

The spectrograph, as may be inferred from its name, is merely a spectroscope adapted for photography. The only dif-

ference between it and an ordinary spectroscope is that the telescope is replaced by a camera. Usually there is no reticle provided in the spectrograph, measurements being made directly upon the plate. Comparison spectra (254) are nearly always used.

250. Resolving Power

The resolving power of a spectroscope is the smallest difference in wave-length which the instrument can separate into individual slit images. Increasing the magnification of the telescope will give a greater separation of the lines, but no advantage is gained by increasing the magnification beyond the resolving power of the prism or grating, for if the images of the two given wave-lengths are not resolved, magnification can do nothing but make the single image wider.

The resolving power of a prism is given by:

$$\text{Resolving Power} = \frac{\delta\lambda}{\lambda} = \frac{1}{t}\frac{\delta\mu}{\delta\lambda} \qquad (42a)$$

where $\delta\mu$ is the increment of refractive index corresponding to an increment of wave-length $\delta\lambda$, and t is the effective thickness of the prism. The resolving power of a grating is expressed by:

$$\text{Resolving Power} = \frac{\delta\lambda}{\lambda} = \frac{1}{mn} \qquad (42b)$$

where n is the order of the spectrum and m the number of lines utilized on the grating

251. Diffraction Gratings

The ruling engine, or machine for ruling diffraction gratings, is one of the most precise mechanical instruments to be found. It must scratch, with a diamond point, about 75,000 perfectly parallel straight lines, about 2″ long and all of the same depth and contour. All these lines must be precisely spaced, about

1/25,000″ apart. This represents about 2¼ miles of precise grooves. Gratings have been made up to 35,000 lines per inch. The largest gratings ever made, to the best of the author's knowledge, are two 15,000 line gratings 4″ x 7″. Each of these gratings contains 105,000 lines, or a total of seven miles of rulings. Ruling a grating may take several days, during which no adjustment of any kind may be made to the ruling engine or the diamond point.

Collodion casts of gratings, made by flowing a thin film of collodion onto a ruled grating and then floating it off on water and mounting on a glass slide, are rather easily made, and are quite satisfactory for all but quantitative purposes. These *replica* gratings are very inexpensive.

252. Infrared and Ultraviolet Spectrographs

The regions of the spectrum outside the region of visible light are accessible to the grating spectrograph, since photographic plates will record wave-lengths from 14,000 Å to the shortest known. In these regions, grating spectrographs have certain disadvantages, principally the low reflectivity of most metallic surfaces for this light. Prism spectrographs to work in the infrared and ultraviolet must be made with fused quartz or fluorite prisms and optical elements, due to the opacity of glass, especially for the ultraviolet.

In the case of fused quartz elements, difficulties arise from the polarization of the light (chapter XXXIII). Quartz splits a beam of incident light into two refracted beams, traveling in different directions. The prism must be cut so that the *optical axis* is parallel to the base of the prism, and if fused quartz lenses are used in collimator and telescope, their optical axes must be parallel to that of the prism, and further, one must be *right-handed* and the other *left-handed*. The prism must be made so as to eliminate the *optical rotation* of the quartz, which means that either two prisms must be used, or a single prism in the so-called Littrow mounting, in which the light is reflected

from the second face of the prism and returns over its original path. This latter method is the better, because it is impossible to produce two identical prisms, which would be necessary in the former type. The meanings of the terms optical axis, right- and left-handedness, and optical rotation are discussed briefly in chapter XXXIII, in connection with the polarization of light.

Fluorite does not have the polarizing effects of quartz, but it has not been possible to secure it in blocks of sufficient size to produce lenses and prisms. The future should see many adaptations of it in ultraviolet and infrared spectroscopy.

For work in the infrared and ultraviolet, it is not possible to focus directly upon the light to be recorded. In the case of the infrared, a focus is obtained by a visible line, and for the ultraviolet, focusing is done on a fluorescent screen. With quartz lenses, the plate must be placed at about 20° to the normal position to correct for the difference in the focal lengths for the different lines.

253. X-ray Spectra

While X-rays are not usually considered to be really optical phenomena, they are part of the electromagnetic spectrum, which includes visible light, and their spectra may be studied by the same type of instrument as are the more common wave-lengths, so that they are worthy of mention here. It is not possible to rule a diffraction grating sufficiently fine to produce X-ray spectra, but Nature has provided exceedingly fine gratings in the crystalline structure of certain minerals, where the crystals occur in parallel layers of the order of 1/100,000″ thick. Such crystals are used in ordinary grating spectrographs (without lenses, of course) to produce spectra in the X-ray region, which must, of course, be studied with the aid of photography.

254. Comparison Spectra

The most accurate method of determining the wave-lengths of unknown lines is by the method of differential measurement

from a comparison spectrum. The light from a laboratory source, whose spectrum is accurately known, is allowed to illuminate half the slit of the spectroscope, while the other half is illuminated with light from the test source. Thus two spectra are seen in the telescope or are recorded on the photographic plate, and wave-lengths present in both spectra can be immediately identified. Also, a differential reading from a known to an unknown line can be made upon a suitable reference scale, or directly in the case of a photograph.

The method of comparison spectra eliminates the effect of any error in the adjustment of the instrument or any error in the scales. The spectrum of iron is most frequently used as a comparison spectrum, because of the many distinct lines and because of the accurate determination of the wave-lengths of a large number of the lines.

255. Modern Spectroscopy

The spectroscope or spectrograph which may be seen in a modern physical laboratory or astronomical observatory bears little resemblance to the basic instruments described and illustrated above. Most modern gratings are concave reflection gratings, mounted according to the Rowland method, and nearly all work is done by photography.

A modern high-dispersion spectrograph consists of a suitable source (electric arc, spark, or furnace), a slit, and a concave grating, all mounted on the circumference of a large circle, which may be 35 feet or more in diameter. The remainder of the circle is represented by a track, around which one or many photographic plates may be mounted, to record a portion of the spectrum produced; or a strip of motion picture film may be passed around the entire track and an exposure made of the complete spectrum produced by the grating, which will, of course, contain all the different orders of spectra on both sides of the normal beam. In this way, a spectrum over 100 feet long may be obtained from a single tiny specimen. On such a

spectrum, there may be hundreds of thousands of lines, no one of which is exactly reproduced by any other substance.

The spectrum, of course, of the near X-ray regions (below 2900 Å) to which air is opaque, must be recorded in a vacuum, so an apparatus similar to the spectrograph described above, but representing only a narrow sector of the circle, is enclosed in a huge vacuum chamber for work in this region. The grating is mounted on an axis so that any part of the spectrum may be brought onto the photographic plate.

256. The Spectroheliograph

No discussion of the spectroscope would be complete without mention of the invention of Dr. George Ellery Hale, which goes under the imposing name of *spectroheliograph*. It was mentioned in (221) that the structure of the sun was that of an intensely hot and bright interior, the photosphere, surrounded by a cooler, less dense, atmosphere, known as the chromosphere. It was pointed out that the photosphere gives a continuous spectrum, from which the cooler gases of the chromosphere extract certain wave-lengths of light, giving rise to the familiar dark lines of the solar spectrum.

Now, these chromospheric gases, although cooler than the photosphere, are by no means cool by terrestrial standards. They are hotter (about 5000°C) than anything known on earth. They radiate light themselves but, since they absorb light from only one direction, from the interior of the sun, and radiate in all directions, the light of those particular wave-lengths passing along the line to the earth is reduced, the absorption overshadows the radiation, and the Fraunhofer lines appear. These dark lines are dark only by contrast. There is a considerable amount of light even in the center of a dark line.

If we permit the image of the sun to fall upon the slit of a spectrograph, each line in the spectrum produced is really an image of a long, narrow strip of the sun, all alike, but images in different wave-lengths occurring at different places.

As we allow the image of the sun to drift across the slit, each of the spectral lines gives successive images of contiguous strips of the sun's surface. If we select some particular wave-length of light, and allow this light, and this light only, to pass through a second slit onto a photographic plate, we can, by moving the plate synchronously with the image moving across the first slit, build up on the plate a complete image of the sun taken in one specific wave-length of light (fig. 149).

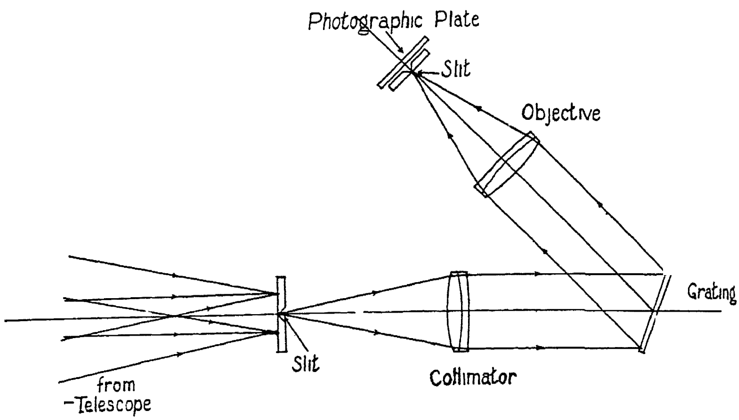


FIG. 149

The spectroheliograph

If we select the center of a dark line of hydrogen, for example, our picture will have been taken with the light emitted by the hydrogen in the chromosphere, and will indicate the distribution of this element there.

A more interesting application of this instrument is in the study of the violent disturbances on the sun's surface known as prominences. Great clouds of hot gases shoot out hundreds of thousands of miles from the surface. These prominences cannot be observed with an ordinary telescope, since they are lost in the glare of the main body of the sun, but they are easily seen in the *spectrohelioscope*.

The spectrohelioscope (fig. 150) is the spectroheliograph adapted for visual use. Instead of the image drifting across the slit, it is rapidly shifted across it about 50 times per second, by a rotating prism or other suitable device, thus permitting visual observation as through a telescope when a second prism, synchronized with the first, is placed in front of the eyepiece. The speed is too great for the eye to detect flickering.

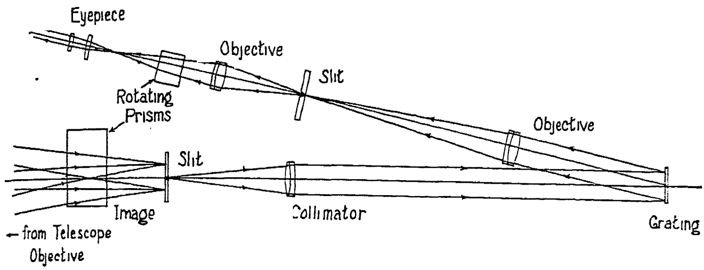


FIG. 150

The spectrohelioscope

A further application of the spectroheliograph goes under the even more impressive name of the *spectroheliokinematograph.* Its name is descriptive, however, meaning merely a spectroheliograph adapted for motion picture photography. It produces motion pictures of the sun's constantly changing surface, and has led to many important conclusions in astronomy and physics.

CHAPTER XXIII

THEODOLITES

257. Purpose

The theodolite is often called a *transit,* although the technical definition of a transit is essentially a theodolite in which the telescope may be turned on a horizontal axis through 180° or more. The term transit also refers to certain astronomical instruments used for the determination of time, which we have no space to discuss here.

Theodolites are used in the surveying of land, essentially in the performance of three distinct functions: to measure horizontal and vertical angles, to determine magnetic azimuth, and to establish a level line for the purpose of determining land contours.

258. The Use of Theodolites

Angles are measured through rotation of the telescope on its axes, accurate scales being provided for measurement of angles in both horizontal and vertical directions. Magnetic azimuth (angular distance from magnetic north) is determined with the aid of an accurate compass. A level line is established with the aid of a sensitive level attached to the telescope tube.

259. Principal Parts

The principal parts of a theodolite are: the *base,* the *horizontal scale and mechanism;* the *compass*; the *vertical scale and mechanism;* the *telescope* (fig. 151).

The telescope is mounted upon a horizontal shaft to which is attached the vertical circle and mechanism. The bearings

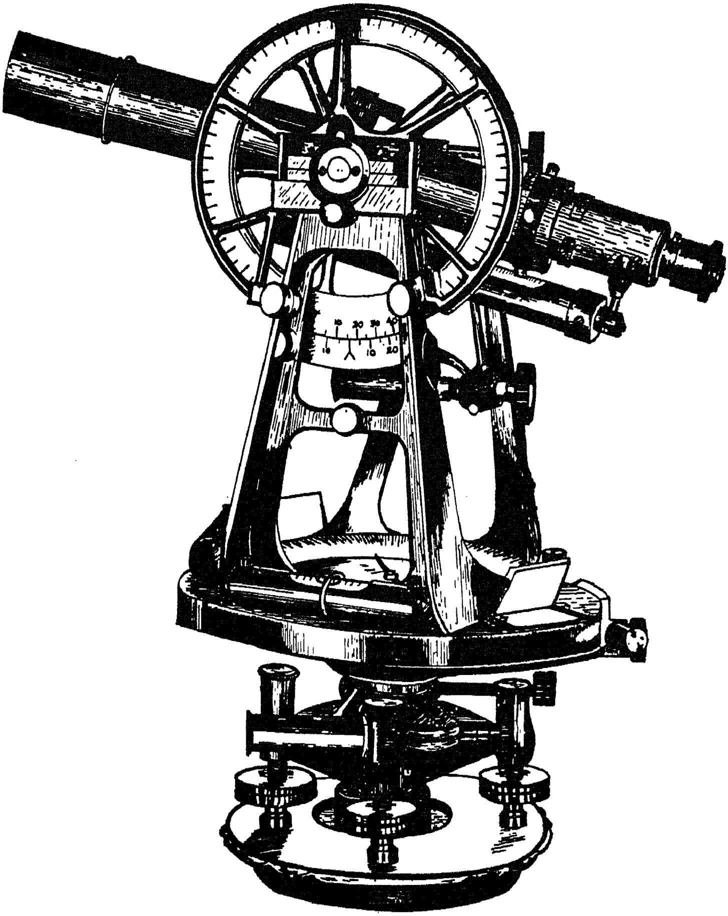


FIG. 151

The theodolite

for this shaft are set upon pillars which rest on the horizontal circle. This circle, together with the pillars, rotates in a vertical plane. The compass is contained in the horizontal circle. The entire instrument rests in a ball and socket, and a three- or four-point support is provided for leveling.

The important specifications of the instrument are that the vertical and horizontal axes shall meet in a point and be mutually perpendicular, and that the optical axis of the telescope be perpendicular to the horizontal axis of the instrument; also that, when the instrument is in use, the horizontal and vertical axes shall be truly horizontal and vertical.

260. The Base

The base contains a ball which fits into a socket in the tripod head. The usual type of mounting of the leveling screws is shown in fig. 152. In leveling the instrument, the horizontal circle is rotated until one of the level vials is parallel with the

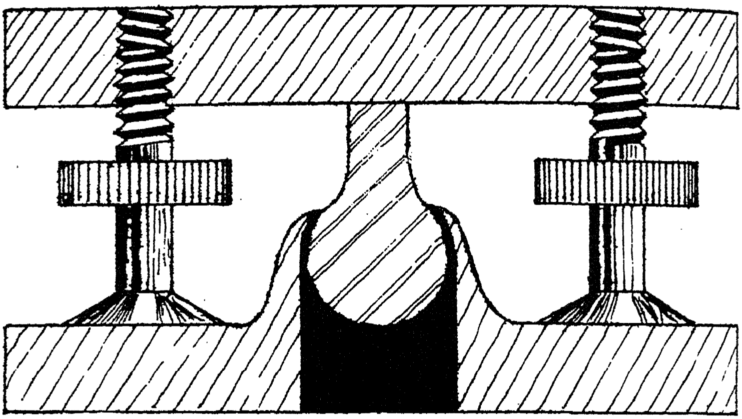


FIG. 152

Ball and socket joint

line joining two opposite leveling screws. These two screws are adjusted, one being screwed upward and the other downward, until the instrument is level in this direction. The other two leveling screws are then adjusted against the other level. Both bubbles should now center in all positions of the circle.

Under the center of the tripod head is a support for a plumb bob, in order that the instrument may be centered over a given

spot. The four-point support is the most common, although three-point support is sometimes found in instruments used for astronomical observations, it being sturdier and less subject to temperature effects. It is much more difficult to level an instrument with a three-point support.

261. The Horizontal Circle

The horizontal circle consists of two parts, the circle and the vernier plate. The circle rotates inside the vernier plate, and is graduated throughout 360° on the upper face, usually in ½° marks. The vernier plate has a vernier scale (264) for reading angles on the circle. The vernier usually has 30 divisions, reading to 1′ of arc, although verniers occasionally read as close as 10″. The vernier plate carries the pillars for the telescope and the compass box. Both table and plate rotate on conical bearings, and clamps and tangent screws (265) are provided on both. The vernier is usually read through a window in the plate assembly, so that dust and moisture may be kept away from the scales and bearings. Horizontal circles range from 5″ to 30″ in diameter, 10–12″ being an average for an instrument of considerable precision. The larger the circle, of course, the more easily the fine graduations may be read, although little if any increase in mechanical precision is attained.

Certain theodolites, known as direction instruments, are of extremely high precision, and are equipped with micrometers instead of verniers. The horizontal circle is rotated by a worm and worm wheel mechanism, instead of a tangent screw. The worm knob carries a circular graduated scale. These instruments occasionally measure to 1″ of arc (fig. 153).

262. The Vertical Circle

The horizontal shaft is mounted in adjustable trunnions on the pillars attached to the vernier plate. The shaft carries a circle or sector, graduated to ½°, usually. A vernier on the

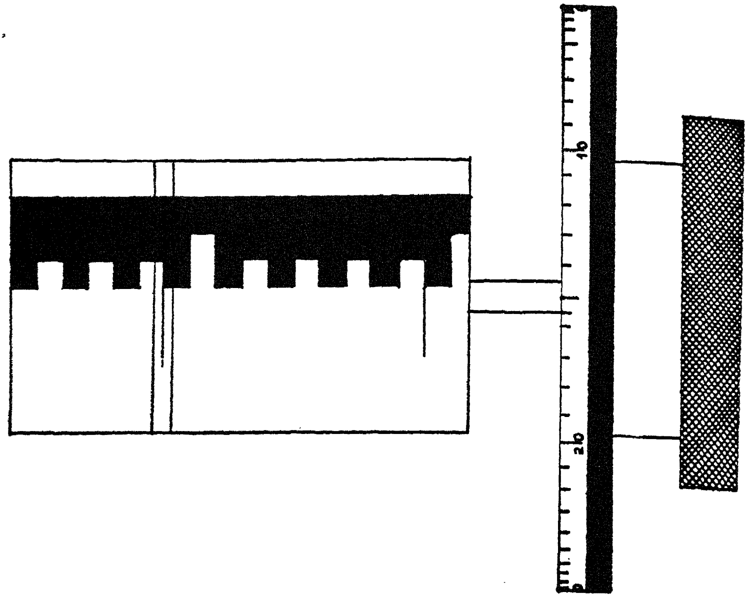


FIG. 153

Micrometer scale found on precision theodolites

pillar gives readings to about 1′ on this vertical circle. The horizontal shaft is also equipped with clamp and tangent screw

263. The Telescope

The telescope of a theodolite is of the usual terrestrial type, including a reticle. It usually provides for a terrestrial eyepiece, ordinary eyepieces being provided for occasional position-finding by celestial objects, for which the telescope becomes an ordinary astronomical telescope. These ordinary eyepieces in this case are usually known as *celestial* or *inverting* eyepieces. The telescope is usually focused by moving the objective lens on a rack and pinion, this method eliminating parallax (367) for close objects. Sometimes an *internal focusing* type is found, in which the construction of the objective is that

of a telephoto lens (181), focusing being accomplished by moving the rear, diverging component on a rack and pinion. Magnification of theodolites varies from 4X to 20X, the aperture rarely being greater than 1″ (fig. 154).

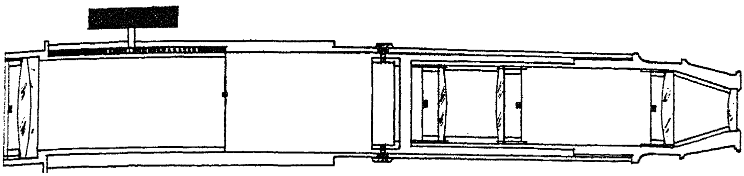


FIG. 154

Theodolite telescope and focusing system

The reticle always contains vertical and horizontal cross hairs, which are carefully adjusted to this position, and sometimes contains *stadia* lines (138). Theodolite reticles are usually made from spider web, although when the instrument is to be exposed to extremes of temperature or humidity, fine platinum wire may be substituted. Etched reticles are not generally found in theodolites. The reticles are made adjustable for centering (fig. 155).

264. Vernier Scales

A vernier scale is a device for reading a graduated scale more closely than it is divided. Its principle is as follows: a short scale is made, containing the number of divisions into which it is desired to divide each division of the main scale. These divisions are so spaced that they are contained in a length occupied by the same number of divisions of the main scale, less one (fig. 156).

Suppose a scale, marked in ½°, and a vernier to read to 1′. Then the vernier will contain 30 divisions, contained in a length equal to 14½° on the main scale. If, now, the index of the vernier coincides with 0° on the scale, then no other line on the vernier coincides with any line on the scale except the

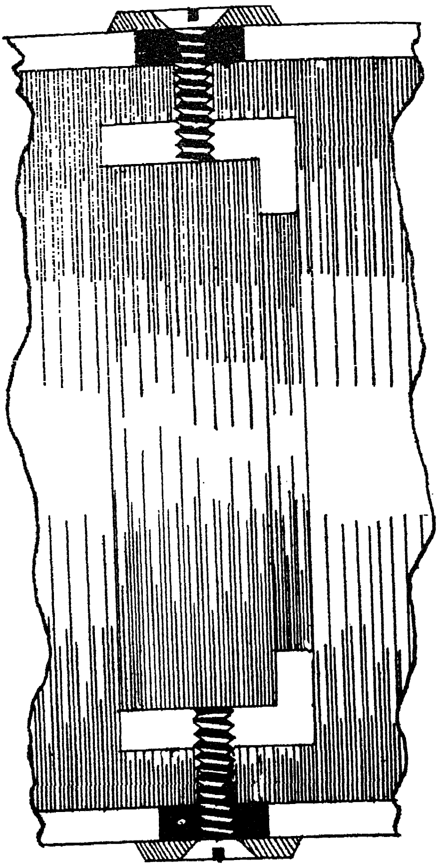


FIG. 155

Mounting of theodolite reticle

30′ line. But, if the scale is shifted back 1/30 of a division, then the 1′ mark of the vernier will coincide with the ½° mark on the scale. If the scale is shifted half a division, then the 15′ mark on the vernier will coincide with the 7° mark on the scale.

Thus the vernier provides a means of measuring fractional

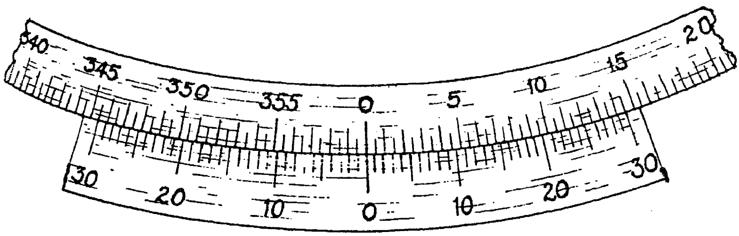


FIG. 156

Vernier scale

divisions of the scale, and the reading of the vernier is the value of whichever of its marks coincides with *any* mark on the scale. This reading is, of course, to be added to the reading given by the nearest point of the scale below the index of the vernier. The vernier shown in fig. 156 provides for both plus and minus readings.

265. Tangent Screws

The tangent screw method of fine adjustment is found almost universally on theodolites. It consists merely of a collar to which is attached an arm. The arm rests between a spring plunger and a screw. Rotating the screw moves the arm through a small arc, turning the shaft through a similar arc. The collar is connected with a clamp, in order that the shaft may be rendered free to move easily for coarse adjustment (fig. 157).

266. Associated Instruments

There are many special and simplified types of theodolites. One of the most common is the *engineers' level,* which contains merely the features of the theodolite necessary for the establishment of level lines. The horizontal axis and the horizontal and vertical circles are omitted.

The *alidade* is a telescope similar to that of a theodolite, mounted upon a flat base. It is used in connection with a

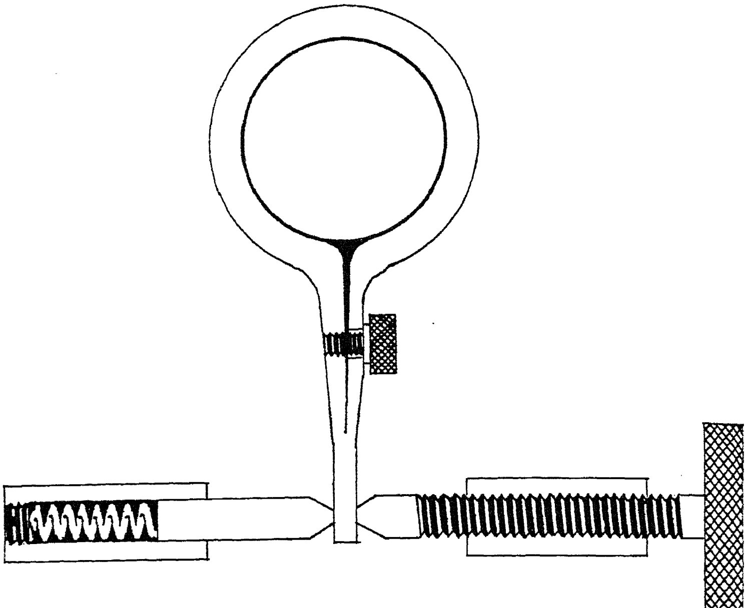


FIG. 157

Clamp and tangent screw

plane table, a drafting table for outdoor use in map-making, etc.

There are, of course, many different types of theodolites and levels, and many attachments and accessories, but the theodolite, as a whole, is probably more standardized in function and design than any other optical instrument. It is also one of the most delicate of instruments, and most subject to damage from rough handling. It should be inspected and adjusted more frequently than is usually customary.

The quality and efficiency of a theodolite depends on the accuracy of its scales and the precision of its adjustments. It is perhaps the most finely adjusted optical instrument intended for outdoor use; therefore, it requires an unusual degree of care and attention while in operation, and should be used only by an experienced person.

CHAPTER XXIV

Miscellaneous Instruments

267. General

The most common types of optical instruments have been discussed in the preceding chapters. These, of course, exist in many forms, and represent those most frequently found. There are many other optical instruments, adapted for specialized purposes, a mere list of which would occupy many pages. Some of these, however, are of more or less general use, and while not of as universal application as telescopes and microscopes, for instance, are still worthy of brief mention. We shall, therefore, enumerate a few more optical instruments in this chapter, although it is not our intention to cover *all* optical instruments. In this respect, it is our purpose to describe the function and optical principles of the instruments and not to give details regarding their use and operation.

268. The Sextant

The sextant (fig. 158) is a portable instrument for the measurement of horizontal and vertical angles, and finds its chief use in navigation of ships and aircraft. It is really a portable theodolite.

The principle upon which the sextant operates is that of combining two fields of view, representing two lines of sight, by means of mirrors, the telescope remaining in a fixed position. There are three main parts to a sextant: the frame, or limb, which carries the arc with the graduated scale and the horizon mirror; the index arm, which carries the vernier and the index mirror; and the telescope. The sextant was originally composed of 1/6 of a circle, from which it derived its name, but modern

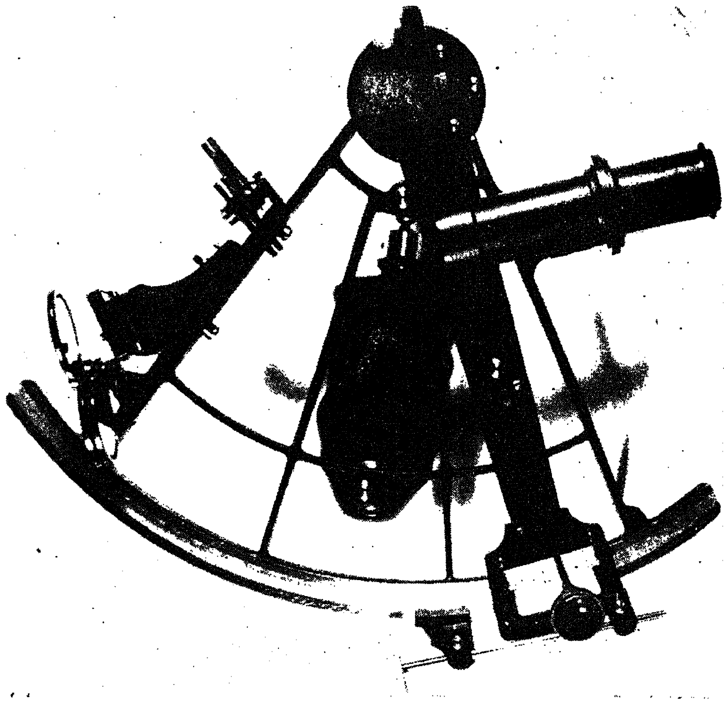


FIG. 158
The sextant

sextants usually contain an arc about 75° in length. Some instruments have a somewhat shorter arc, and are occasionally known as *octants*.

The arc has a radius of 8–10″, and is very finely graduated, the vernier frequently reading to 10″ of arc. For this reason, vertical angles measured with a sextant are usually somewhat more precise than those measured with a theodolite, the least count on a theodolite vertical circle being usually 1′. A magnifier is customarily provided on a sextant for reading the vernier.

The horizon mirror, which is carried on the frame in a fixed position in front of the telescope, is silvered over half its area, the other half being clear. The position of this mirror is so adjusted that the center of rotation of the index arm is reflected along the optical axis of the telescope. The index mirror, attached to the index arm, is silvered, and so adjusted that when the index is at zero on the scale, the two mirrors are parallel. The telescope is rigidly attached to the frame.

In using a sextant, the index arm is rotated until the two objects between which an angle is being measured coincide in the field of view, one object being seen directly along the optical axis through the clear section of the horizon mirror, the other object being seen by means of the silvered half of the horizon mirror and the index mirror. In astronomical measurements of altitude for navigational purposes, the two objects are the horizon and a celestial body, often the sun. The index mirror is adjusted until the lower limb of the sun appears to rest upon the horizon, and then a correction is applied to the measured altitude to bring the angle to the center of the sun's disk. Filters are provided for use on the sextant when the sun is being observed.

The sextant is not limited to the measurement of the altitudes of celestial bodies, however, although this is its principal use. It is possible to measure the angle between any two objects, by holding the limb of the sextant in the plane in which the angle is being measured, which may call for the sextant to be held horizontally, or even upside down.

The geometrical principle of the sextant is diagramed in fig. 159. A study of the figure will show that the angle x, through which the index mirror has been rotated, is ½ the angle y between the directions of the two lines of sight. The scale of the sextant is, therefore, graduated with half-degrees of true arc marked as whole degrees, so that a 75° arc suffices to measure angles up to 150°.

When no clear horizon is visible, it may be necessary to use

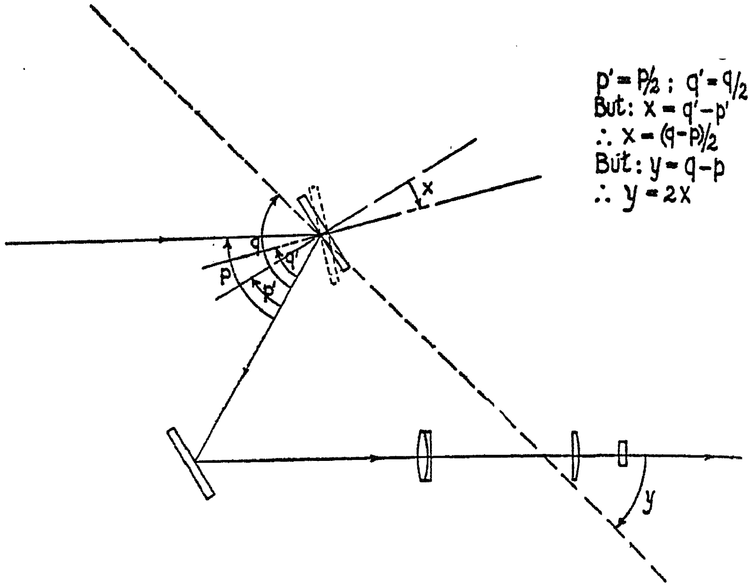


FIG. 159

Geometrical principle of the sextant

an *artificial horizon,* which is nothing more than a level reflecting surface, such as a still pool of water or mercury. Coincidence is obtained between two images of the celestial body, one through the index mirror, and the other through the horizon mirror and reflected in the artificial horizon. A study of fig. 160 will show that the angle which is measured by the instrument in this case is twice the actual altitude of the object.

Before using a sextant, it is necessary to establish the index error. This is the angle between the two mirrors when the index is set at zero or, what is the same thing, the reading of the vernier when the two mirrors are parallel. The two mirrors are set parallel by sighting upon a distant object, preferably a celestial body. When the two images of the same object

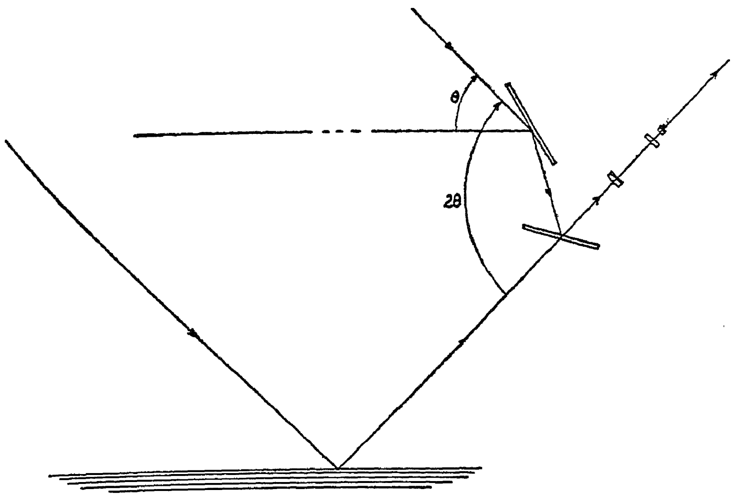


FIG. 160

Measuring altitude with an artificial horizon

coincide, the mirrors are parallel, and the index error is read off the vernier. This is to be added to or subtracted from all measurements made with the instrument.

The *bubble sextant* does not require a horizon, and is thus much favored for the navigation of aircraft, where the altitude of the plane introduces an appreciable difference between the direction of the horizon and a true level line. In this instrument, the image of a level bubble is superimposed in the field of view containing the object, which is seen by direct vision. The bubble is then rotated into a level position and the angle read on a scale.

269. The Polarimeter

The polarimeter (fig. 161) is an instrument for determining the optical rotation (see chapter XXXIII) of certain substances in solution. It makes use of polarized light for this purpose. The instrument consists, optically, of a polarizer, an

analyzer, and a telescopic system. The sample is sealed in a tube and placed between the polarizer and the analyzer.

The principle of measurement of optical rotation is to pass polarized light through the sample and, using the analyzer, determine at what rotatory angle the plane of polarization of the analyzer is perpendicular to the plane of polarization of the light emerging from the sample. At this position, of course, the light is completely extinguished. The angle between the plane of polarization of the polarizer and the perpendicular to the plane of polarization of the analyzer then gives the degree of rotation taking place in the sample, from which a determination of the constitution and the concentration of the sample may be made.

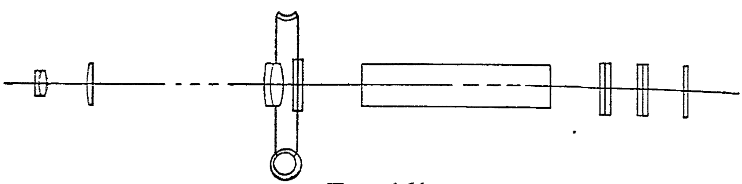


FIG. 161

Optical system of the polarimeter

In practice, however, complete extinction of the light cannot be judged accurately by the eye, and it is customary to make the measurement by matching the brightness of two fields of view, a determination which can be made with extreme accuracy. There are two ways in which the field of view may be divided for such a measurement.

One method is to introduce, in the polarizer, a sheet of quartz, which covers half the field of view, and performs a certain rotation of the plane of polarization. The analyzer is then adjusted until the brightness of the light rotated by both quartz and sample equals the brightness of that rotated by the sample alone. Due partly to the difficulty of producing such quartz plates to the proper specifications, but principally to

the necessity of using the exact wave-length of light for which the quartz has been prepared, this method is infrequently used.

The more common method is to provide a double polarizer, one component of which is placed behind the other and covers either one-half or one-third of the field of view, and whose plane of polarization is placed at a known angle to that of the main polarizer. Formerly, the most common method of producing and analyzing polarized light was by means of the Nicol prism, a double prism of calcite (see chapter XXXIII), but with the development of Polaroid, a sheet of optically parallel crystals of iodosulphate of quinine embedded in plastic, it has been possible to construct polarizing instruments which are much more compact than those using Nicols.

The analyzer, and usually the telescope as well, rotate by means of a worm and worm wheel mechanism with a scale reading in degrees to determine the rotation necessary to match the brightness of the fields of view. In order to obtain a sharply divided field of view in the polarimeter, it is, of course, necessary to focus the telescope upon the polarizer.

The polarimeter is used in measuring concentrations of cane sugar, invert sugar, dextrose, etc., as well as in the determination of the sugar concentration in urine. When it is used specifically for the measurement of sugar concentrations and has a scale graduated directly in percentage of sugar, it is known as a *saccharimeter.*

270. The Colorimeter

The color absorption of certain substances is a reliable measure of their concentration in a solution, and the colorimeter is an instrument for making determinations of such absorption. Like the polarimeter, the method is to match two fields of view. The divided field in the colorimeter is obtained by the use of a double prism, *biprism,* which obtains light from the sample to be tested and from a standard comparison solu-

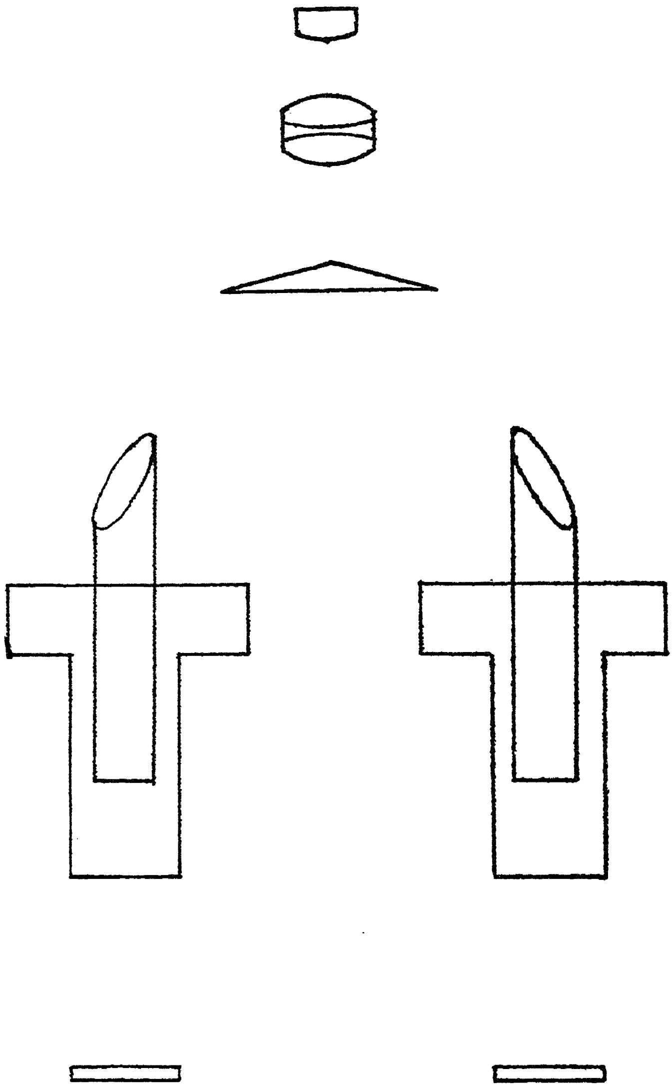


FIG. 162

Optical system of the colorimeter

tion. The solutions are held in adjustable glass cups, in each of which is a glass plunger (fig. 162).

By raising or lowering the cups the amount of solution beneath the plungers is varied, and in this way the two fields of view may be matched. Each plunger has its top cut at an angle, to refract the light into the biprism, and is raised and lowered by a rack and pinion with a scale on the knob indicating the depth of solution beneath the plunger.

The light source is customarily built into the instrument, and means is provided for balancing the illumination beneath the two solutions. The eyepiece of the instrument must be highly corrected, especially for color, and usually contains a triplet field lens for this reason. The instrument is used most frequently for measuring concentrations of uric acid, determination of sugar content and others in blood.

271. The Cystoscope

The cystoscope (fig. 163) is characteristic of a numerous group of optical surgical instruments for the examination of the interior of the body. The bronchoscope, resectorscope, urethroscope, and others are of the same general principle and construction, although each has its specific purpose which is reflected in its design.

FIG. 163

Optical system of the cystoscope

The optical system of the cystoscope (fig. 163) consists of the objective lens system, the so-called middle lenses and the eyepiece. The objective system is furnished in several different types (fig. 164), providing for different directions of view. The middle lenses are for the purpose of transferring the image through the considerable length of tube, and a Dove

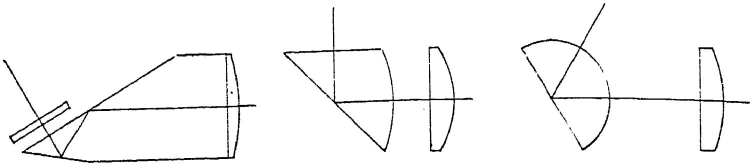


FIG. 164

Various types of cystoscope objectives

prism in the eyepiece corrects for the inversion produced by the reflecting surface in the objective.

As the entire instrument, due to anatomical considerations, can be only a few millimeters in diameter, and the telescope must occupy no more than half the space in the sheath, in order to leave room for the surgeon's manipulative instruments, the optical system is of extremely minute aperture. The instrument usually has several interchangeable telescopes of various lengths and diameters. A light is provided in front of the objective for illuminating the cavity which is being examined.

272. Comparators

The instruments known as comparators are used in laboratories and industrial plants to make precise measurements of small distances. They work on the principle of the *optical lever,* a light ray used as a measuring lever. The principle of the tilting mirror is often used; this was noted in the sextant, where we saw that rotation of a mirror through a given angle would rotate a reflected beam of light through twice that angle.

Fig. 165 shows a simple type of optical comparator. In this instrument, a projection lens focuses a small disk of light upon a graduated scale, the disk containing a central dark line. A mirror is included in the optical system, and this is tilted by a slight movement of the spindle, operating through a long mechanical lever. Between the movement of the spindle and

that of the image on the scale there is a magnification of about 1000 times.

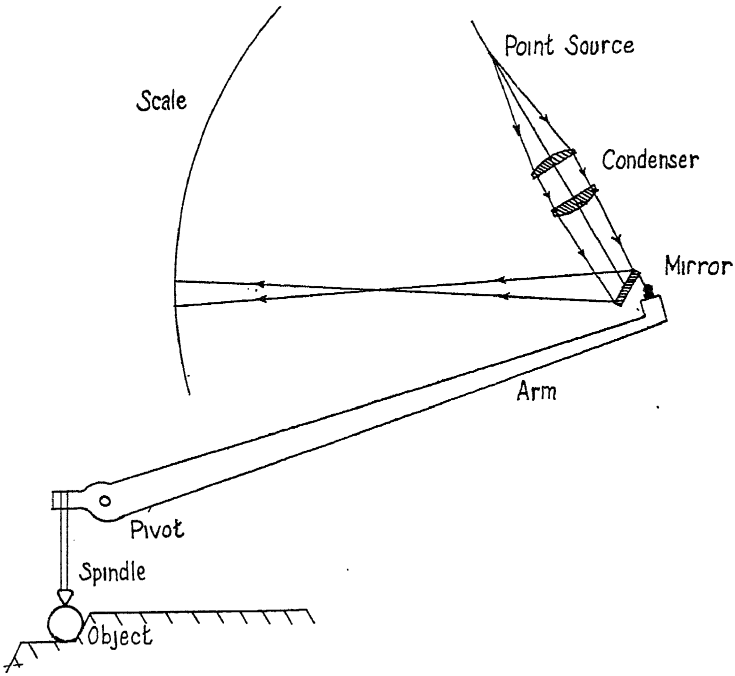


Fig. 165

Simple type of optical comparator

Fig. 166 shows a somewhat more elaborate type, in which there are two reflections from a tilting mirror. In this instrument, the image of a scale is projected by a collimator lens, is deflected twice by the tilting mirror and once by a fixed mirror, and is observed through the view telescope, which contains a reticle marked with an index line. The magnification of this instrument may be 10,000 times.

It can be seen that comparators have an extremely high degree of precision, but also that their range of measurement must be small. It rarely exceeds a few thousandths of an inch

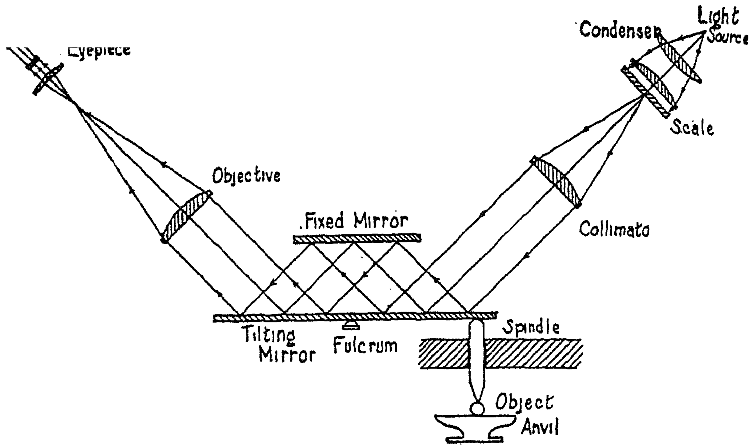


FIG. 166

Laboratory type of optical comparator

on either side of the zero setting. The spindle is adjustable to measure a specific dimension, and the instrument then indicates variations from this dimension in a plus or minus direction.

These instruments are used in production inspection of machine parts having extremely close tolerances, in the checking of tools and gages, etc. In the second type shown, the scale reads directly in hundred-thousandths of an inch, and millionths may be estimated with considerable accuracy.

273. Contour Projectors

An instrument similar in function to the comparator is the contour projector, or projector comparator (fig. 167). This instrument projects a silhouette of a test part on a translucent screen, where it may be compared with a carefully prepared chart or pattern. The optical system is that of an ordinary projector (chapter XXI) with condenser and projection lenses. By means of prisms and lenses, the image is produced upon a screen at a convenient position for observation.

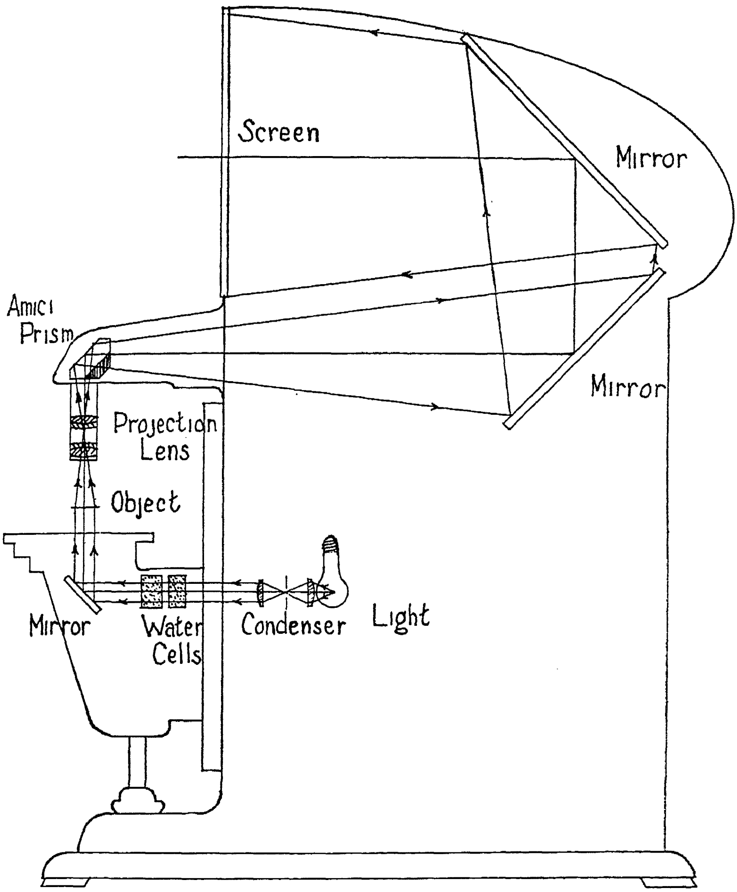


FIG. 167

Optical system of the contour projector

Contour projectors do not possess the high degree of magnification of dimensions produced by the optical lever comparators, the magnification of a contour projector ranging from 8 to 100 times. Interchangeable projection lenses are usually provided for variation in the magnification.

274. The Interferometer

By making use of the principle of the interference of light (chapter XXXIII), instruments known as interferometers are capable of making measurements of ultra-precision, well below a millionth of an inch.

Technically, any instrument which uses the principle of light interference to make measurements is an interferometer. There are a large number of types, all of which operate on the principle of dividing a beam of light into two parts, each of which pursues a separate optical path, being finally brought together in the field of view. Interference of the two beams produces the familiar fringe pattern. The position of the fringe pattern will change as the difference in the optical paths of the two beams changes, each fringe width representing half a wavelength difference in the optical paths.

Fig. 168 illustrates the interferometer designed by Michelson, which represents a good example of the general type of instrument. The mirror A is movable. The second plane-

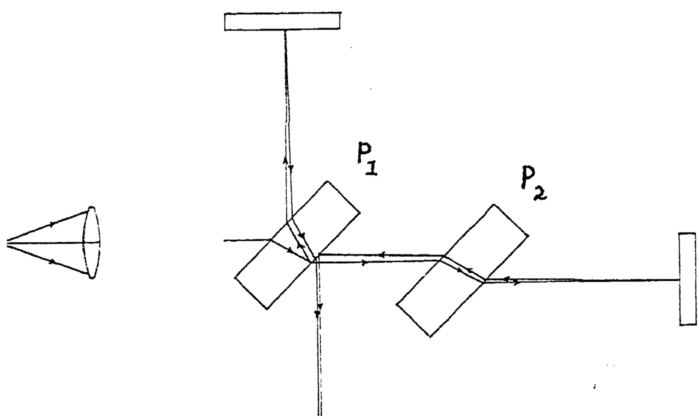


FIG. 168

Optical system of the Michelson interferometer

parallel plate, P_2, is provided so that the light path through glass of both beams is equal.

The interferometer must be provided with monochromatic light in order for the fringe pattern to be produced.

275. The Ophthalmometer

The ophthalmometer (fig. 169) is an instrument used for measuring the radius of curvature of the cornea of the human eye. It consists of an illuminated object which is reflected in the cornea and a short-focus telescope by which this image in the cornea is examined. Contained in the telescope is a suit-

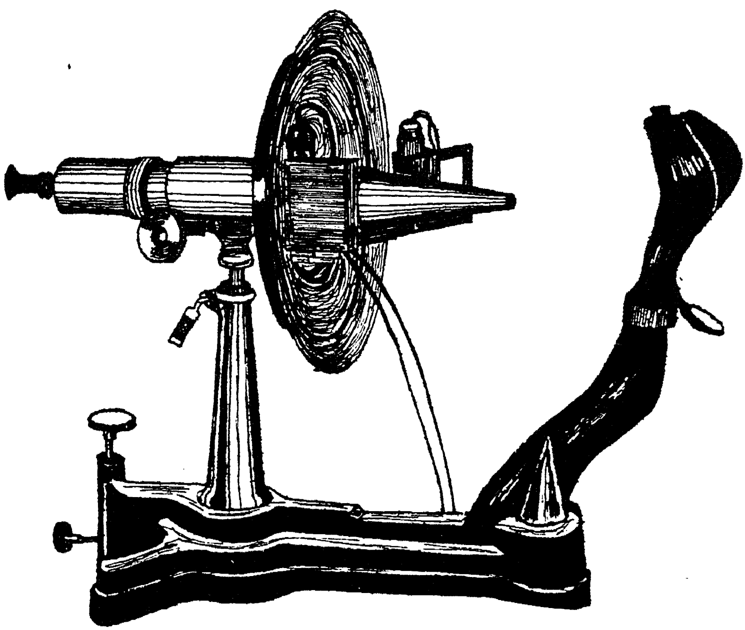


FIG. 169

The ophthalmometer

able device for doubling the light beam, the Wollaston polarizing prism being the most commonly used device. By adjusting

the instrument until the two separated images just touch at their adjacent edges, a measurement is made of the size of the image produced in the cornea and hence of the radius of curvature of the latter. The adjustment may be made by changing the size of the illuminated object or by an adjustment in the doubling mechanism, depending upon the design of the ophthalmometer in question.

CHAPTER XXV

Military Instruments

276. Classification

Military optical instruments may be classified in three categories: 1. Observation, 2. Fire Control and 3. Signaling.

Observation instruments include telescopes, cameras, aerial and terrestrial, periscopes, and binoculars. Fire control instruments are those used for the direction and observation of gunfire and form the largest group. Very little signaling apparatus is of an optical nature. Navigational instruments are, of course, also in use by the military services, but these are rarely of special type, and are merely duplicates of the instruments used commercially for the same purposes, nor are most of them optical.

277. Observation Telescopes

The observation telescopes used for military purposes are of the common terrestrial type (chapter XVII), sometimes found with interchangeable eyepieces for variation of magnifying power, which is usually between 10X and 30X. Requirements of portability restrict the size of these instruments. Naval observation telescopes tend to attain somewhat larger sizes than those used by land forces, because the portability requirement is not present. It would be ridiculous, however, to build a really large telescope for terrestrial observation, since the range of vision is limited to 6–12 miles (depending upon the altitude of the observer) by the curvature of the earth.

278. Cameras

Military forces use many common varieties of hand and motion picture cameras in various types of work. In the Japanese forces, in particular, miniature cameras are very frequently found on the common soldier, although this practice has never attained military favor in this country. Aerial cameras are much more important today than ever before, and most artillery fire is dependent upon up-to-the-minute aerial photographic surveys. Aerial cameras sometimes reach huge proportions, with lenses up to 12 inches in diameter and focal lengths of 80–100 inches. This is necessary in order that sufficient detail may be disclosed on photographs taken from altitudes of 20,000 to 30,000 feet. The problem of variation in temperature of the air inside and outside the camera becomes important in high-altitude work, and many secret devices have been developed to eliminate or neutralize the effects.

A great deal has been accomplished in recent years in the development of the technique of aerial mapping with the stereoscopic camera, and this has been of great assistance in the study of enemy terrain and in the establishment of points of bombardment or attack.

279. Military Restrictions

It must be remembered that in the following sections we are dealing with very delicate subjects. Every effort has been made by the author to tell everything that is public knowledge and to withhold all items of information not believed to be known to the enemy's technical experts.

There have been many new developments in optical instruments which must remain confidential until after the present war. The instruments and principles which we shall discuss are known to and in use by the armies and navies of all the world at the present time.

280. Periscopes *

In the last war, when trench warfare was prevalent, observation periscopes were widely used. These were usually about

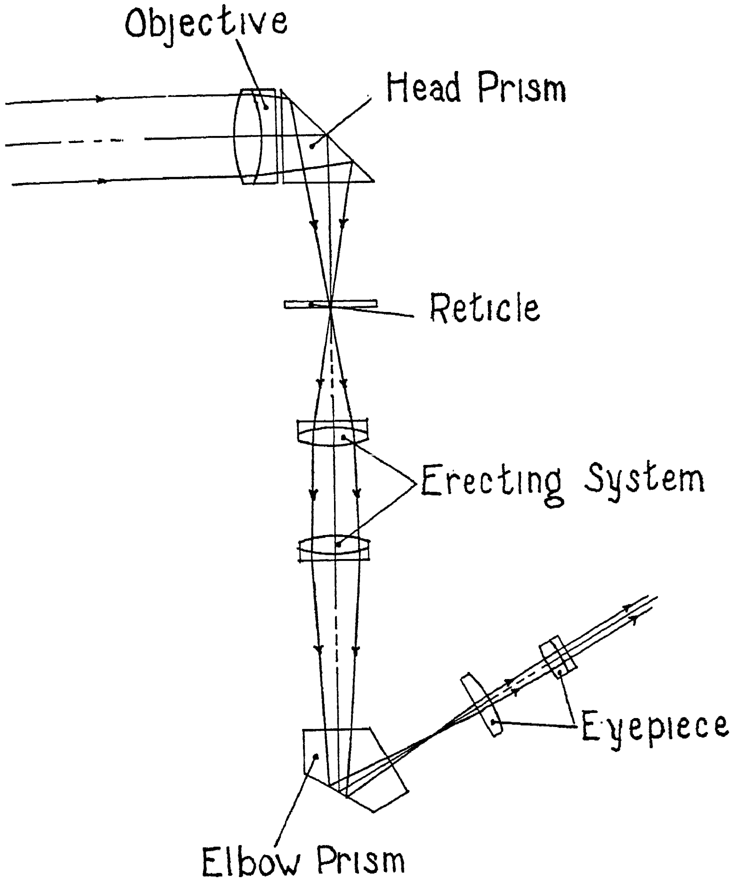


FIG. 170

Optical system of trench periscope

* Strictly speaking, the term *periscope* applies only to panoramic instruments (291). The technically correct terminology for an instrument which has a fixed direction of view and an optical axis displaced in the vertical direction is *episcope*.

two to three feet in length with optical systems as shown in fig. 170. With the new techniques in warfare, these periscopes have more or less passed out of use.

Periscopes, however, are the modern method for vision from tanks, having replaced vision slits as safer and more satisfactory. Tank periscopes usually contain no lenses, merely two mirrors with protecting cover glasses (fig. 171). Some periscopes, however, used for gun pointing, have complete sighting telescopes contained inside (fig. 172).

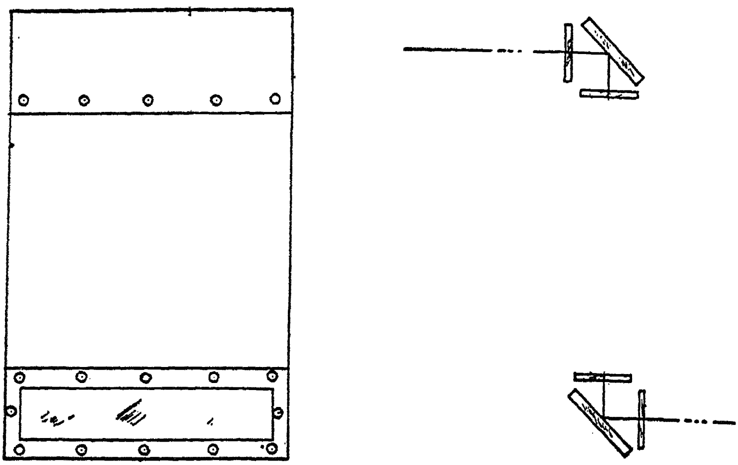


FIG. 171

Modern tank periscope

Unlike most other optical instruments, the field of view of periscopes for tanks is usually rectangular, much longer in the horizontal than in the vertical direction.

281. The Submarine Periscope

The submarine periscope is entirely another matter. There are two important properties to be attained in a submarine periscope, it must be sufficiently long to allow the submarine to remain well submerged while the periscope is far enough

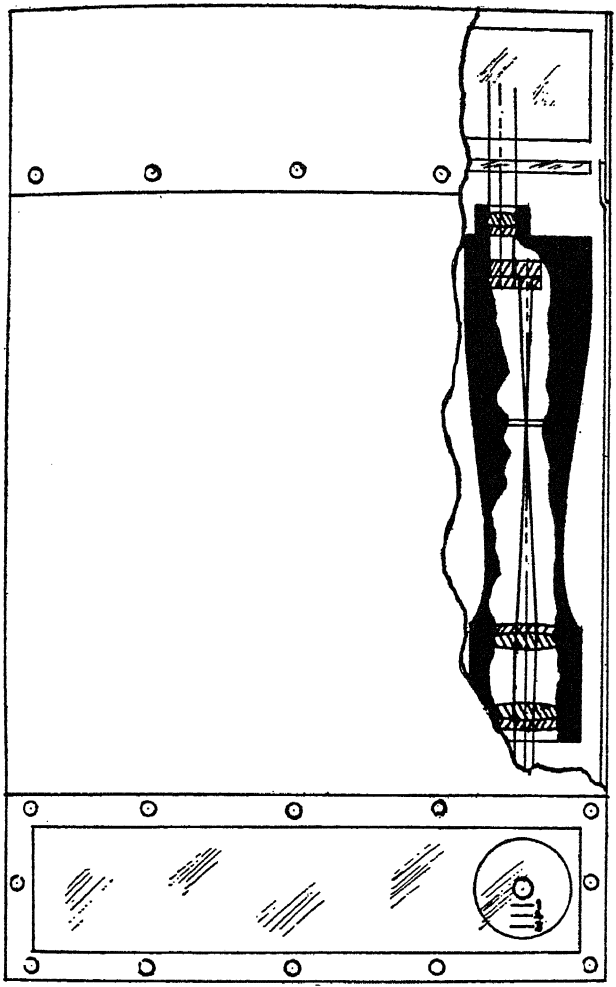


FIG. 172

Telescopic system in tank periscope

above the surface to permit clear observation, and the size of the head must be as small as it can possibly be made, to reduce its visibility to a minimum. A lens 6″ in diameter stick-

ing out of the water would be visible by a keen observer for miles.

In order to provide a reasonably large field of view (at least a few degrees) a telescope must be made with a fairly short focal length. But this is inconsistent with a long tube length (about 40 feet in a submarine periscope), and the difficulty is overcome by the use of successive optical systems, similar to erecting systems, which give little or no magnification, but merely serve to transfer the image farther along the tube, as shown in fig. 173. The same requirement was met in the same way in the cystoscope.

For changes in magnification in submarine periscopes, it is common practice to provide interchangeable objectives of different focal length, which may be moved quickly into position. Periscopes, of course, contain reticles for the purpose of estimating range of targets as well as direction.

In some designs of submarine periscopes, there is an annular field of view surrounding the main field, which gives a view throughout 360°. This is accomplished through the use of toroidal reflecting and/or refracting surfaces in the head of the periscope.

282. Binoculars

Binoculars have been discussed in considerable detail in chapter XX. Military binoculars are in no way different except that they usually contain a reticle in *one* of the telescopes. Two reticles would be unnecessary and would lead to insuperable difficulties in collimation (chapter XXIX). These reticles usually provide for the measurement of small angles in both horizontal and vertical planes and occasionally provide scales for the estimation of *relative* ranges, since binoculars are commonly used in the control and observation of gunfire (fig. 81). Binoculars used by the land forces are usually 6X30. Naval binoculars are sometimes larger and more powerful,

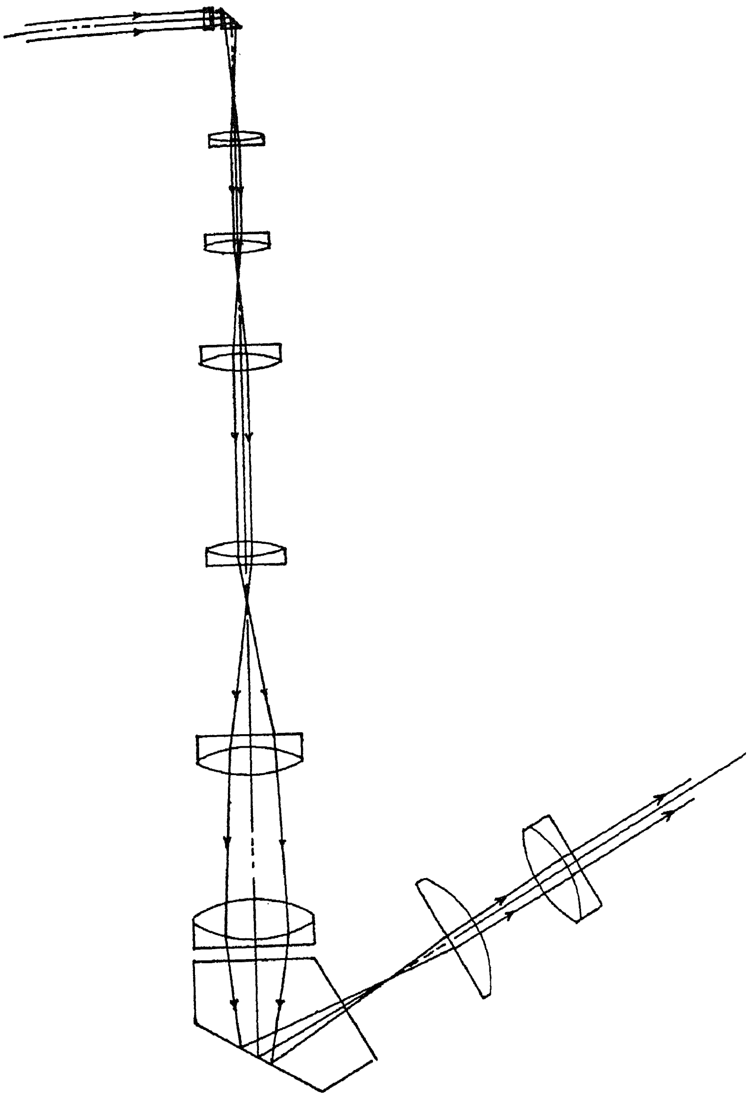


FIG. 173

Optical system of the submarine periscope

but they are frequently mounted on permanent supports, and not held in the hand.

283. Navigation Instruments

Optical instruments are used for both nautical and aerial navigation. The sextant has already been discussed in chapter XXIV. It is necessary, of course, to use bubble sextants in aerial navigation, since the horizon is no longer a suitable criterion. Also in common use in aerial navigation is the *drift-meter,* which is essentially a terrestrial telescope provided with a suitable reticle by which the navigator may make measurements of the plane's drift with respect to the earth.

FIRE CONTROL INSTRUMENTS

284. Classification

Fire control instruments, i.e., instruments for the direction and control of gunfire, artillery, naval, anti-aircraft, fall readily into two groups: 1. Those instruments mounted directly upon the carriage of a weapon, that is, sights, telescopic or otherwise. 2. Those instruments used for observation and plotting which are set up independently of the weapon itself, including range finders and measuring instruments. These classes are known, in military terminology, as *on-carriage* and *off-carriage* instruments.

ON-CARRIAGE INSTRUMENTS

285. Gun Sights

A gun sight is an instrument or device used for the purpose of pointing the barrel, or tube, of a gun in the proper direction. The simplest and most common example is, of course, the familiar open sight on the ordinary rifle. Its function is to provide a small marker which, when lined up with a V-slot and the eye, will indicate the direction in which a gun is pointed.

If the line joining the V-slot or rear sight with the front sight is made parallel to the axis of the gun barrel, the extension of this line will meet the target at a point the same distance from the point of impact of the bullet as the line of sight is from the axis of the gun barrel (usually a fraction of an inch in an ordinary rifle).

This assumes that the projectile travels in a straight line, which is not true. However, it is nearly true for a short distance. If the projectile is to travel a long distance, however, the actual form of its path must be taken into account. This is a parabolic arc, the resultant of the velocity of the projectile, the force of gravity, the pressure of the air, and several other factors of minor importance. The result of all this is that the gun must be aimed *higher* than the target in order for the projectile to hit its mark. This is clear to anyone who has thrown a baseball, who knows that if he is to throw it to a distant player, he must start it off toward a point well over the player's head.

It is evident that, in order to maintain the line of sight *on the target,* while pointing the gun upward, *elevating* it, we must *raise the rear sight.* Some device, with graduations, is usually provided for raising the rear sight. The distance the projectile will travel, the *range,* is computed for the particular gun and ammunition, and the sight system graduated accordingly.

286. Telescopic Sights

Clearly, the open sight described above is not going to be very accurate, small variations in direction being imperceptible in the sight picture, but having a considerable effect on the point of impact of a projectile at a considerable range. Some advantage is gained by replacing the rear sight slot with a tiny hole, or *peep,* but in order to establish a really accurate line of sight, an optical instrument is necessary. The most common is the telescopic sight.

A telescopic sight is merely a terrestrial telescope fitted with a suitable reticle and *bore-sighted* with the gun barrel so that the optical axis of the telescope is parallel* with the axis of the bore of the gun. Such an instrument has three distinct advantages over an open sight. First, there can be no question as to the position of the line of sight, there is no "sight picture" to concern the marksman, and there is no obstruction of the field of view by the sights and the gun itself. Secondly, the instrument usually magnifies so that the target is much more plainly visible in the telescope than to the naked eye. Thirdly, the position of the eye is not critical, the image of the field of view is fixed with respect to the reticle, and the eye may be shifted at will without disturbing this relationship ** (the eye, of course, must remain within the exit pupil).

One important feature of a telescopic sight is that it must have a large eye distance, else the recoil of the weapon will injure the gunner's eye. The usual eye distance is 3–5 inches. This requires a rather large diameter eyepiece, which can lead to the somewhat paradoxical situation of a telescope with a larger eyepiece than objective.

In order to provide a large exit pupil (so that the eye position is not critical), the magnifying power must be kept small. It rarely exceeds 5X, and is usually less than this.

287. Artillery Sights

Telescopic sights used on artillery of small caliber do not differ essentially from the rifle sights described above. Usually the magnifying power is somewhat less, about 1X–3X, in order to increase the size of the exit pupil and field of view. In the case of an explosive projectile, it is not quite as necessary to hit the *exact* target. In rapid fire weapons used on moving targets, two sighting telescopes are frequently provided. One operator keeps the target against a vertical line in the reticle

* Sometimes the two axes are adjusted to converge at a specific range.
** See *parallax* (367).

by operating the *traverse* of the gun, while another keeps the target on a horizontal reticle line by operating the gun in *elevation.*

In larger caliber weapons, whose range is greater, it is necessary to provide greater magnification, and in order to do this without making the telescope an unwieldy diameter, exit pupil and eye relief as well as field of view must be sacrificed. This brings the gunner's eye closer to the instrument and increases the danger of injury. This is avoided by using an *elbow* telescope, in which the optical axis is turned through 90°, so that the direction of recoil is *across* the gunner's line of sight (fig. 174).

288. Range Correction

Small corrections in elevation for range of target usually are made by reference to the reticle of the telescopic sight. When the gun is elevated, the target drops lower in the field of view, and appears against a line on the reticle indicating the proper position of the target in the field of view for a given range.

Some sighting telescopes are equipped with movable reticles, so that known ranges and corrections for wind velocity, drift, etc., may be "set off" on the instrument and the target then lined up with the center mark on the reticle. In other cases, the corrections are set off by mechanical mountings which adjust the position of the telescope itself with respect to the gun. This is necessary when the correction is large.

289. Collimator Sights

A type of sight favored for rapid fire work is the so-called collimator sight (fig. 175). Its function is to form an image of a suitable reticle at infinity. It consists of an illuminated reticle, a projection lens and a plane-parallel plate. The light forming the image at infinity is bent through 90° by the plane-parallel plate, the final direction of the optical axis being made

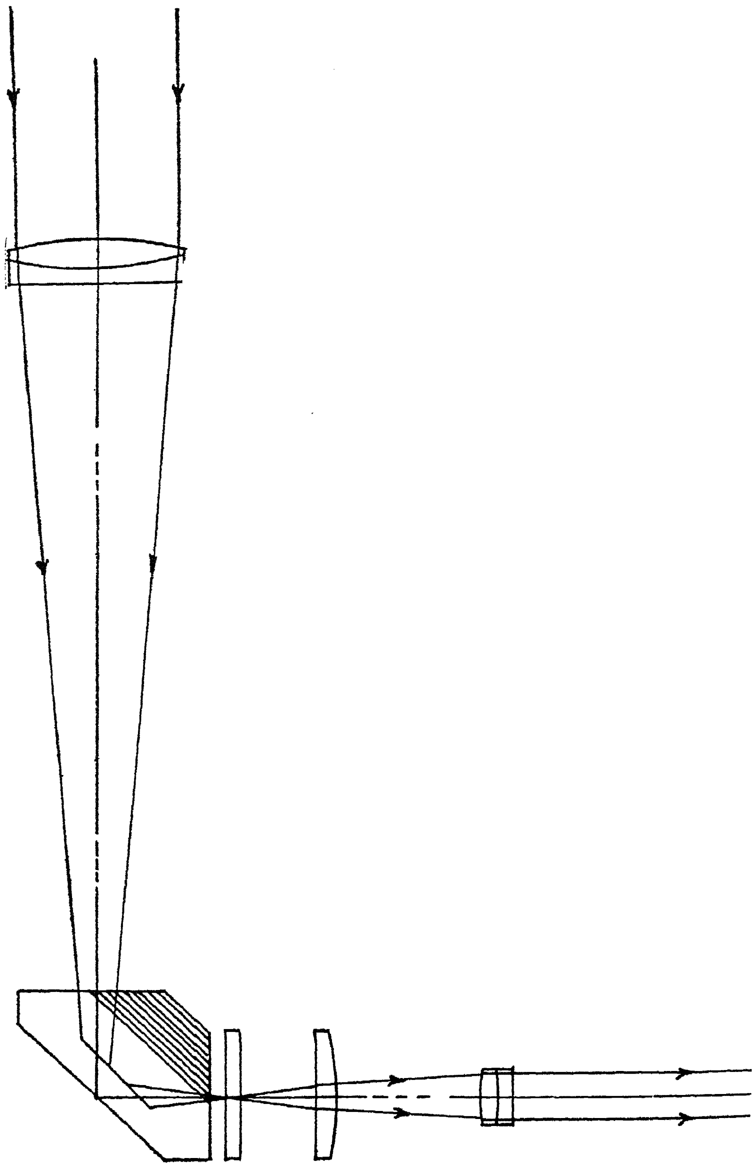


FIG. 174

Optical system of elbow telescope

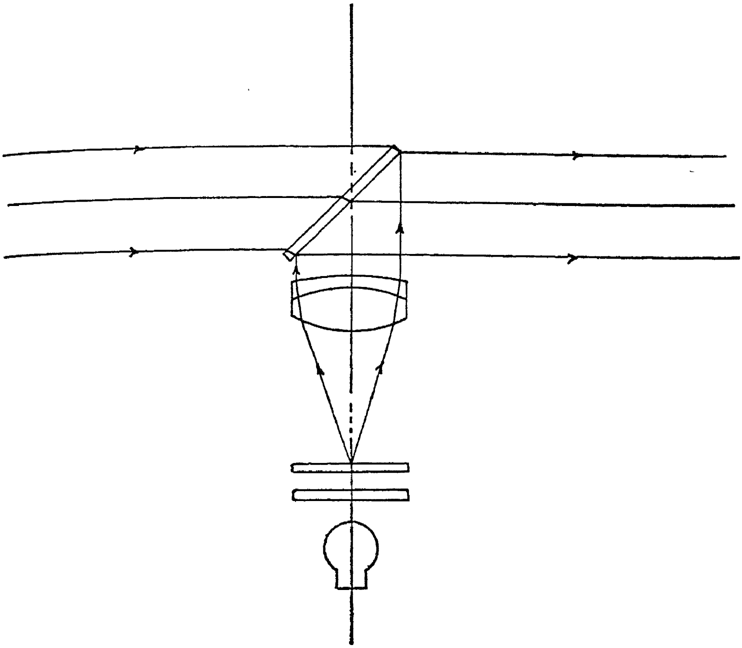


FIG. 175

Optical system of collimator sight

parallel to the bore of the gun. A concave mirror may be used for a projector.

If the eye is placed anywhere in the path of light, an image of the reticle is seen, and the eye also receives light directly through the plane-parallel plate from the target. The exit pupil in this instrument is so large that the problem of eye-distance disappears, and the eye position is unimportant. The eye may be placed at any distance behind the sight and anywhere within a large cylinder of light.

In a simplified type of collimator sight, the projection lens is quite small, and the eye is placed directly behind it. In this case, the view of the target is obtained over the top of the

sight, and the reticle, usually a straight vertical line, is lined up under the target in the same manner as the front marker of an open sight.

290. Indirect Fire

When the target is invisible to the gunner, because of distance or obstructions, the gun must be *laid* (aimed) by sighting upon an arbitrary *aiming point,* which may be and usually is at some direction from the gun different from the direction to the target. It may often be behind the gun. The establishment of this point will be discussed in (294). There is some definitely known angle between the aiming point and the proper direction of the gun barrel, as well as the factor of elevation. An instrument must be provided whose line of sight can be directed at a known angle from the bore of the gun.

291. The Paroramic Telescope

The instrument used almost invariably for such *indirect sighting* is the panoramic telescope. This is essentially a periscope, with right-angle prisms, objective, and erecting system. Usually the lower right-angle prism and erecting system are combined by using an Amici prism (126).

The head prism is so mounted as to be rotated about a vertical axis through 360° and the mechanism is provided with a scale to measure the azimuth between the line of sight of the telescope and the bore of the gun. The head prism can also be rotated through a small vertical arc to correct for any difference in height between the aiming point and the gun.

Now, the principle of equivalence of inversion and rotation discussed in (84) becomes involved. As the right-angle prism in the head rotates with respect to the reticle and the observer's eye, the eyepiece remaining fixed, the field of view also rotates at the same velocity. This can only be corrected by rotating the observer himself through the same angle (as would be done in a submarine periscope) or by a correcting prism.

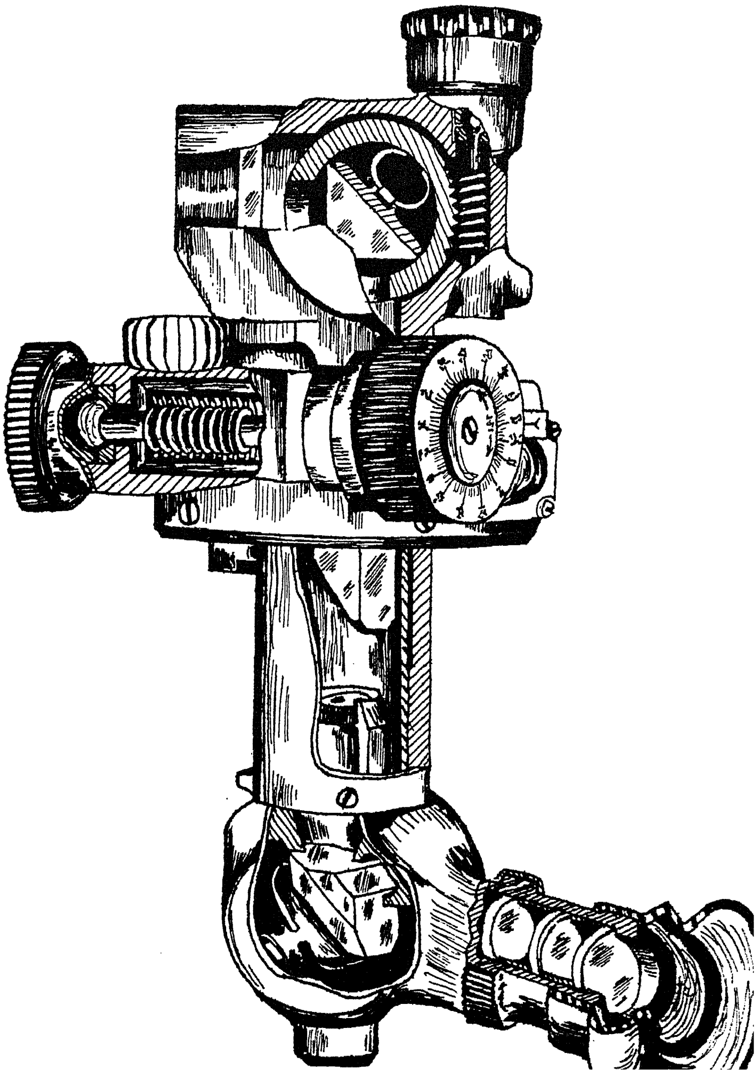


Fig. 176

The panoramic telescope

It was seen in (84) that by rotating the plane of inversion through an angle θ, the effect produced was equivalent to a rotation of the field of view through 2θ. Therefore it is evident that if we introduce inversion in one plane by an element that can be rotated through half the angle through which the head prism has been rotated, full correction for rotation of the field will be accomplished. This rotating element, however, must retain the optical axis in the same direction, that is, it must produce no deviation.

The most common sort of prism answering the specifications of inversion in one plane and no deviation is the Dove prism (88), and it is this prism which is most commonly found in panoramic telescopes. A gear mechanism is provided linking the rotating Dove prism with the head prism in a 2 to 1 ratio. The Dove prism has certain disadvantages, however, principally due to its necessarily great length. It absorbs a great deal of light, and because of the aberrations attendant upon the entrance of the light at an angle to the entrance face, it must not be placed in a converging beam of light. So it must be placed *outside* the objective where it severely restricts the field of view unless it is made impracticably large. Any optical element or system which produces inversion in one plane without deviation will serve the same purpose as does the Dove prism in this instrument, and it may be placed anywhere in the optical system that other conditions will permit. One German panoramic design achieves rotation of the field by the use of cylindrical lenses.

292. Bombsights

The aerial bombsight is a type of direct sighting instrument. Very little can be said about the construction of such instruments, but the basic principles are obvious to anyone. A sighting telescope with a suitable reticle must be so mounted with graduated scales as to permit setting off corrections for time of flight, velocity, wind-drift, and numerous other factors.

The secret part of such an instrument lies, of course, in the mechanical innovations developed to transmit from mathematical formulae to mechanical movement the various necessary corrections to the line of sight, the mechanisms for controlling the flight of the plane during the bomb run, etc. The optical system is quite ordinary.

293. Aerial Gunsights

The sights used on aerial guns do not differ essentially from those used for similar weapons on the ground. Generally aerial gunfire is at *point-blank* range so that range correction is unnecessary even if there were time for making the correction. Furthermore, in most cases, the range is changing so rapidly as not to permit correction.

In fighter planes, the situation is somewhat different, since the aiming of the guns in a fighter consists of pointing the plane itself at the target. Further, the guns of most fighter planes are mounted in the leading edge of the wings, and set to converge at a definite range. The pilot is provided with a telescope of low magnification and large field of view, equipped with a reticle upon which, by knowledge of the size of his quarry, he can determine at what instant he has reached the range at which his guns converge. Such a reticle might consist of merely a dot and a circle.

The mounting of larger and larger caliber guns in planes has led to the development of various types of sighting devices, some quite complicated and all, of course, secret.

OFF-CARRIAGE INSTRUMENTS

294. Azimuth and Range Determinations

In the case of indirect artillery fire (290), if the battery commander is provided with aerial maps of the region concerned, it is a simple matter for him to plot on them the range of the target and the azimuth correction from the arbitrarily

placed aiming point. This is the usual modern method, and all the data will have been carefully worked out long before the battery moves into its position. In the absence of such convenient maps, however, measurements and computations must be made upon the ground. This is the purpose of *off-carriage* instruments.

A location for the battery commander's post is selected from which must be visible the target, the battery, and the aiming point. It is then necessary to measure angles and distances among these points and perform the trigonometric calculations to yield the required azimuth of the gun from the aiming point and the required elevation of the gun.

295. Measuring Instruments

Two instruments are necessary to secure the data, the range finder, which is discussed in chapter XXVI, and some sort of theodolite for angular measurements.

The instruments used by military forces for such angular measures are the azimuth instrument and the aiming circle. The former is merely a sturdily constructed theodolite, with worm and worm wheel mechanisms instead of tangent screws. The customary horizontal and vertical circles and leveling screws are provided. The aiming circle is an even more compact instrument, and contains a compass for the determination of magnetic azimuths. With respect to a theodolite, a sacrifice is made in accuracy for sturdiness, the aiming circle measuring to about 1 mil (1 mil $= 0.0562°$ fig. 177).

Some armies, notably the German, use a periscopic type of instrument, probably on the assumption that by this means the observer may remain protected and concealed while making his observations. In permanent installations, such as sea-coast artillery, more elaborate instruments may be used, and greater accuracy attained. However, in the case of explosive projectiles

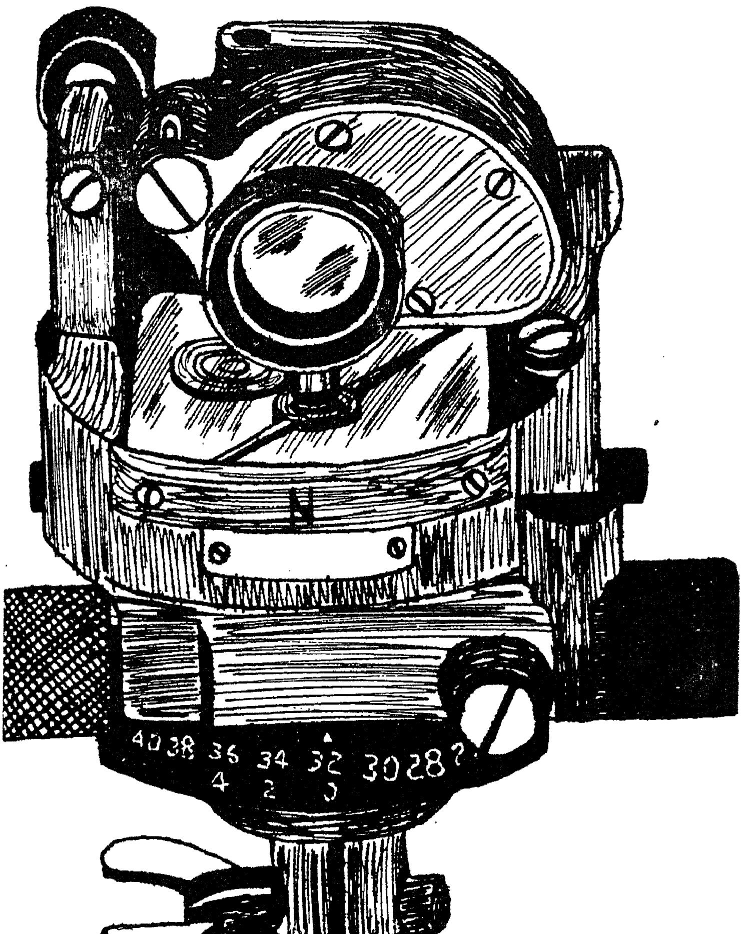


FIG. 177

The aiming circle

of large caliber, extreme accuracy is not essential, a burst anywhere within the immediate vicinity of the specific target being effective.

296. Differential Correction

Time is usually an important factor in military operations, and it is generally considered advisable to make an approximate determination of azimuth and range, fire a few shots, and, after noting the location of the bursts, make the necessary small corrections to bring the gun directly on the target rather than spend a large amount of time in attempting to hit the target centrally at the first shot. This requires observation of fire from the commander's position and an instrument for measuring small angles of *deflection* (horizontal angles) and elevation.

297. The Battery Commander's Telescope

The instrument universally used for this purpose is almost identical with all armies and is called the *battery commander's telescope*. It is a large binocular periscopic instrument with a magnifying power of about 10X–15X, and equipped with a suitable reticle (in *one* telescope only) for measuring small angles. It is sometimes built on a hinge which permits rotation of both telescopes into a horizontal plane, so that it becomes an instrument of considerable stereoscopic power. In any case, some hinge movement is necessary to provide interpupillary adjustment (fig. 178). Binoculars, of course, are often used for observation of fire.

298. Automatic Direction and Ranging

The problems of moving targets of high velocity presented in anti-aircraft fire introduces rapid changes of direction and range which has necessitated the development of devices for the mechanical determination of gun-pointing data at a much more rapid rate than would be possible by ordinary computation. These directors and computers are not optical instruments, except insofar as they contain *tracking telescopes,* and

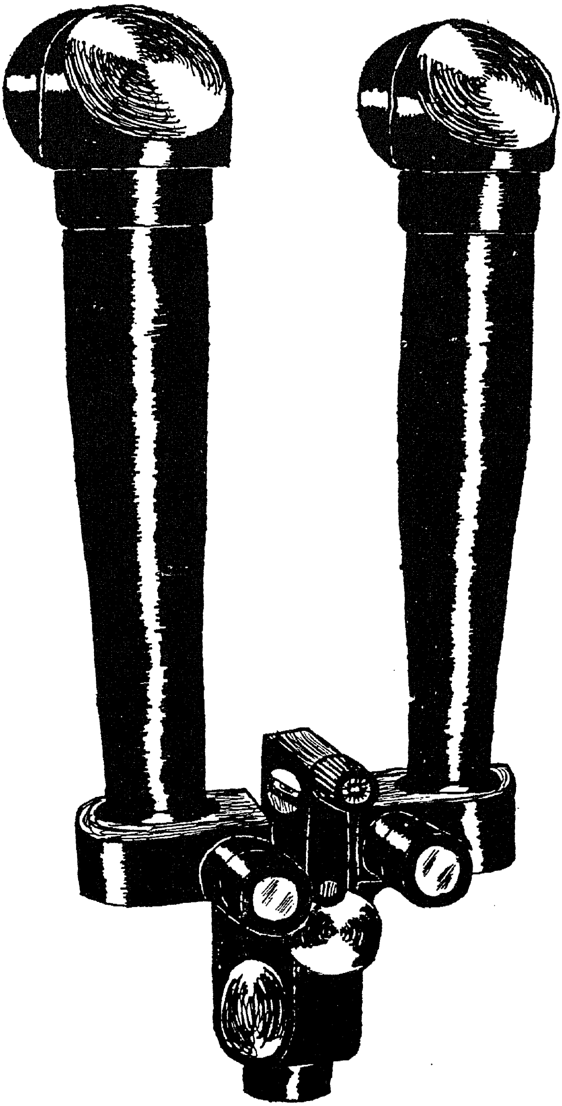


Fig. 178

The battery commander's telescope

are, of course, of a highly confidential nature; they cannot be discussed here. The tracking telescopes are operated on the usual dual principle, one telescope and one operator for azimuth, another telescope and operator for elevation.

CHAPTER XXVI

Range Finders

299. The Range Triangle

We saw in our discussion of stereoscopic vision (208) that there is a definite angle of convergence from the two points of observation upon the target. In the determination of distance, or range, this angle is the basis of the *range triangle.* This is the long, narrow triangle whose base is the line joining the two points of observation, and whose apex angle is the angle of convergence of the two lines of sight, which form the other two sides of the triangle. This is the fundamental triangle for all determinations of distance; it is used by surveyors for triangulation work, by machinists in application of the sine bar, even by astronomers in determination of the distances of the stars.

If b is the base (fig. 179), and angle A is taken to be a right angle, and B is the convergence angle at the target, the range will be given by:

$$r = \cdot$$
$$\tan B$$

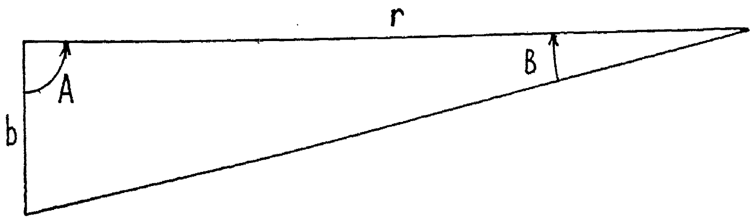


Fig. 179

The range triangle

But since for any practical case, B will be very small, we can use radian values, and write:

$$r = b/B \tag{43}$$

300. The Range Finder, Types

The principle of determining range lies in the measurement of the convergence angle B and the translation of this into a value for the range, r. Thus the simplest possible type of range finder would be an arrangement of four mirrors, in which one end mirror is rotated to adjust for the displacement due to the convergence angle. This is, in principle, the range finder used on cameras. Precise range determination, however, involves two telescopes, whose objectives are separated by the base, b. This is the basis of all range finders, but there are two distinct types with reference to the method of detection and measurement of the convergence angle B. These are the coincidence and the stereoscopic types.

THE COINCIDENCE TYPE RANGE FINDER

301. Displacement in the Field of View

If we have two telescopes separated by a distance b whose optical axes are parallel, and if we then combine the two fields of view into a single field of view divided by a horizontal line, a given object in one field will be displaced laterally with respect to its appearance in the other field in an amount depending upon the base, b, the range, r, and the focal length, f of the objectives. Fig. 180 shows such an arrangement, where penta prisms have been added to the instrument to permit a convenient merging of the two fields of view. The linear value of the displacement will be:

$$l_r = f \tan B, \text{ or, in radians:}$$

$$l_r = fB$$

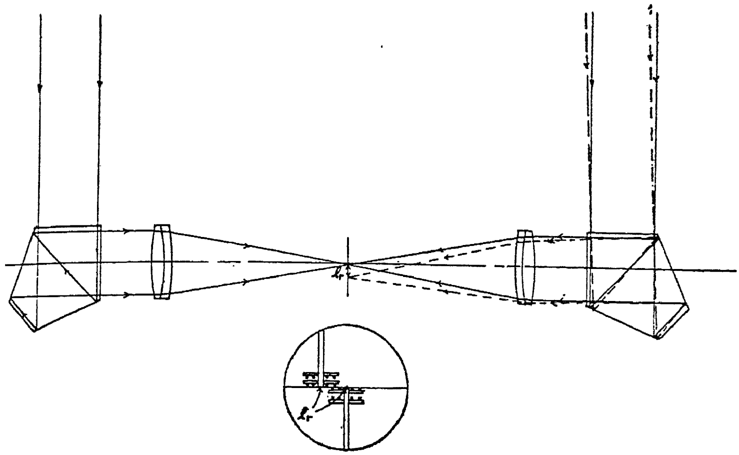


FIG. 180

Principle of the range finder

B being the convergence angle, or, since $r = b/B$, we can write:

$$l_r = \frac{fb}{r} \tag{44a}$$

It would be theoretically possible merely to etch a reticle with suitable markings to measure this displacement and translate it into terms of the range, by:

$$: \frac{fb}{l_r} \tag{44b}$$

but, since the angle is very small, a somewhat more accurate method is provided by the introduction of a device for shifting one of the fields of view until the object appears at the same point in each, that is, until the object is in *coincidence*.

302. Wedges

The concept of deviation immediately suggests a prism. Since the necessary deviation is through an angle of the order

of B, which is very small, the prisms have a very small refracting angle, A, and are usually referred to as *wedges*. The displacement in the field of view by a prism whose deviation is D will be, evidently:

$$e_p = Ds$$

where s is the distance from the prism to the image plane. This is the case for a prism which lies inside the optical system, and, in order for the displacement of the prism to equal the displacement of the image due to the target's range, we must have:

$$l_p = l_r$$

$$Ds = \frac{fb}{r}$$

or, in terms of the range:

$$s = \frac{fb}{D}\frac{1}{r}$$

For an object at infinity, it would be necessary that $s = 0$, which is obviously impossible to achieve under the conditions described.

But, if we introduce a prism in *each* optical system, making one fixed in position and one movable, then the necessary displacement to give coincidence can be achieved by a *change* in the position of the movable wedge. This requires a slight adjustment of our equations (fig. 181).

If we write the equations in differential form, we have:

$$dl_p = Dds$$

whence:

$$ds = \frac{fb}{D}\frac{1}{r} \qquad (45)$$

where s becomes the position for which the displacement is equal to that of the fixed wedge. It will be noted that the

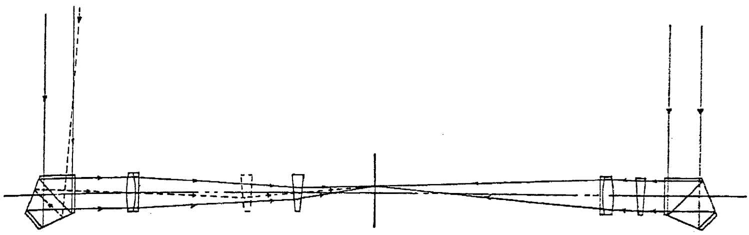


FIG. 181

Optical system of the coincidence type range finder

amount of displacement of the movable wedge necessary to obtain coincidence for a given range may be made as large as desired by making D sufficiently small.

The fixed wedge is usually placed *outside* the objective, in which case its displacement becomes $l_f = fD$, which is independent of the position of the wedge.

303. Rotating Wedges

An alternative method of introducing a displacement equal to that produced by the range of the target is to provide *two rotating wedges outside* the objective. If these two wedges are placed with their bases parallel but opposite, the deviation of one cancels that of the other. Suppose now that one wedge is rotated with respect to the other through the angle 2θ. Consider the bisector of 2θ and its perpendicular, and the components of the deviation of each wedge (fig. 182).

The component of the deviation of the first wedge upon the bisector will be $D \cos \theta$, and upon the perpendicular, $D \sin \theta$. For the second wedge we have $-D \cos (-\theta)$ and $-D \sin (-\theta)$, which may be written $-D \cos \theta$ and $D \sin \theta$. Adding the results for both wedges, we have, for the bisector

$$D' = D \cos \theta - D \cos \theta = 0$$

and for the horizontal

$$D' = D \sin \theta + D \sin \theta = 2D \sin \theta$$

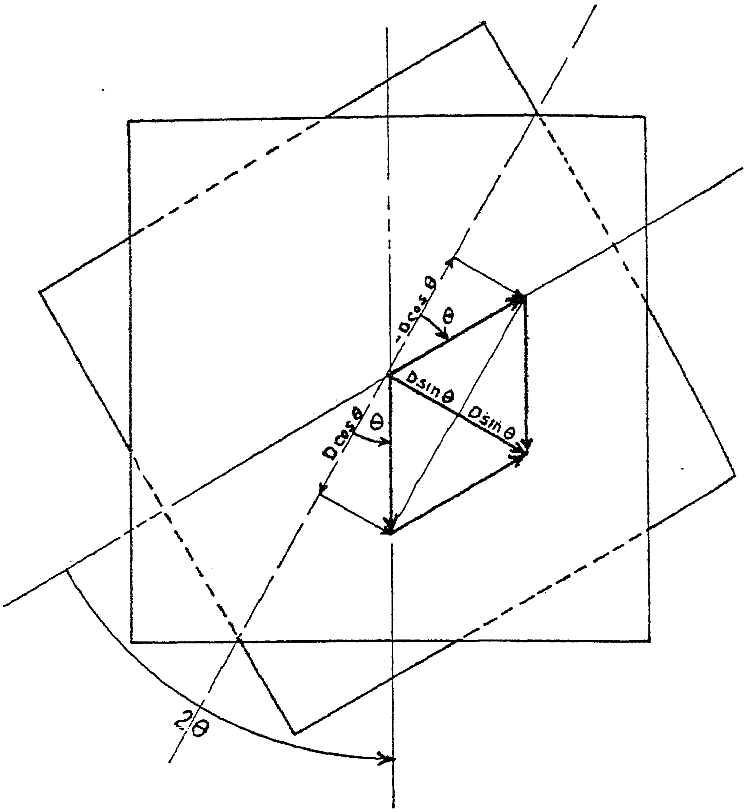


FIG. 182

Principle of rotating wedges

When $2\theta = 180°$, we have $D' = 2D$, the maximum value when the bases of the two wedges are together. If the arrangement is such that the bisector is fixed with respect to the instrument, that is, if both wedges rotate equally in opposite directions, the deviation is entirely in one plane, and the correction for the range displacement can be made. With this arrangement, no wedge is necessary in the other telescope.

304. Correction Lens

It is essential that the magnification of both telescopes be exactly the same, else the coincidence will be affected at all points except exactly in the center of the field of view. This means that the focal length of both objectives must be the same. Since it is difficult, if not impossible, to grind and polish two lenses to *exactly* the same focal length, it is customary to make an objective of a focal length a few millimeters greater than the other, and to provide a *correction lens,* a converging lens of slight curvature, placed behind the objective at a considerable distance from it. By moving this correction lens laterally, changing its separation from the objective, the focal length of the combination can be adjusted exactly to match that of the other, uncorrected, objective.

305. Azimuth Type Range Finder

A slightly different type of coincidence range finder is found in the so-called *azimuth* type. In this type, the focal length of one of the objectives is greater than that of the other, so the magnification is slightly greater in the corresponding field of view. If the instrument is rotated in azimuth, a position somewhere in the field of view will be found for which the difference in magnification exactly equals the displacement due to range. The distance from the center of the field to this point of coincidence is then the basis of the range computation, which is marked upon a suitable reticle.

306. Types of Divided Field

The field of view of the coincidence type range finder can be divided in several ways. If both fields of view are erect, and the top of an object is brought into coincidence with the bottom of the same object, it is known as the *erect* type of field. If the upper field is inverted and the lower field erect, and an object is brought into coincidence with a mirror image of it-

self, the field is known as the *inverted* type (fig. 183). In some range finders, one of the telescopes has as its field of view a narrow strip across the center of the field of view of the other telescope, the strip being inverted and the main field of view erect.

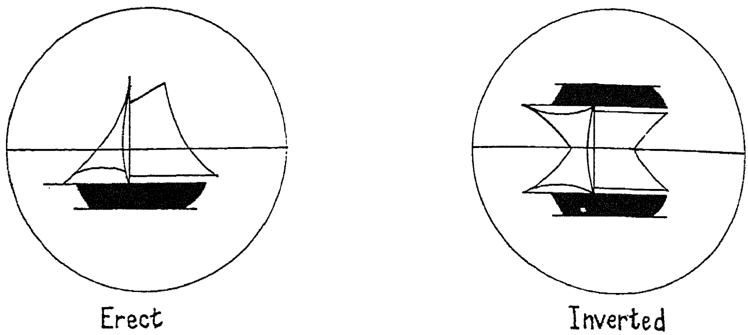


FIG. 183

Erect and inverted field in coincidence type range finder

Certain range finders are constructed on the *super-position* plan, where the fields of view are merged but not divided, and the operator makes the correction by removing *double vision.* The convenience and accuracy of the operation is increased by making the two images in different colors, so that upon superposition the color changes. Any lack of registry is immediately apparent by colored fringes. The effect is heightened by making the two colors complementary, as orange and blue, so the superposition results in gray, and the colored borders due to lack of registry stand out strongly.

307. Halving

The division of the field of view is usually achieved by means of a half-silvered prism. The prism system used just beneath the eyepiece (to accomplish the necessary inversion and the second 90° deviations) contains a surface so placed that the images from both telescopes fall upon it, but from

opposite directions. It is silvered across one-half the image area, so that half of the light from each telescope is reflected and half transmitted.

The dividing line between silver and glass, known as the *halving line,* must be straight and sharp, and the instrument must be so adjusted that the halving line passes through the same points in both images, so that the field of view is divided exactly in half. The adjustment for halving is usually accomplished by a shift of the telescopes with respect to the end prisms, either the *optical bar* (309) or the end prisms themselves being adjustable in position.

308. Penta Prisms

The 90° deviations at the ends of the base are usually achieved by penta prisms, because the penta prism is a constant-deviation prism (88) and this removes the necessity of making precise adjustment in the positions of the end prisms with respect to azimuth. In some range finders, two plane mirrors are used, mounted in the same relation as the two reflecting surfaces of a penta prism.

309. Construction of the Range Finder

The general construction of the coincidence type range finder of the better kind is shown in fig. 184. The two telescopes are mounted in a unit known as the *optical bar,* which is of rigid

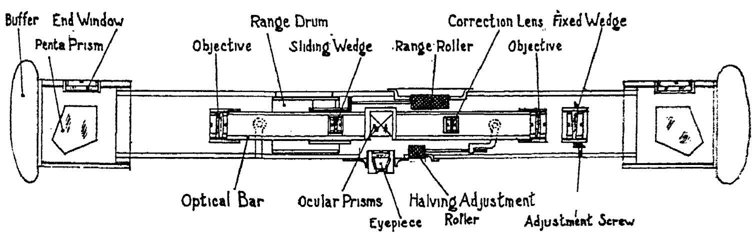


FIG. 184

Schematic diagram of range finder construction

construction and is attached to the outer tube at two points. At one of the points the mounting is in the form of a joint which permits collimation of the optical bar with the end prisms, which are carried upon the outer tube (307).

If a sliding wedge (302) is used, this is contained in the optical bar, and in the tube in front of the objective of the other telescope is placed the stationary wedge. This wedge is adjustable by rotation so as to match its displacement with that produced by the sliding or *measuring wedge* when the latter is in its normal or *infinity* position. If rotating wedges are used, these are placed in the tube in front of the objective of one of the telescopes.

THE STEREOSCOPIC RANGE FINDER

310. Stereoscopic Effect

Stereoscopic power was discussed in (208). Since the range finder contains two telescopes whose objectives are separated by the length of the base, b (actually the separation of the entrance faces of the penta prisms), if it is made binocular it becomes an instrument of very great stereoscopic power. Since the stereoscopic effect is dependent upon range, it is necessary only to provide a means of measuring the stereoscopic effect to achieve a range reading.

311. Reticles

The measurement is achieved by special reticles. A reticle is placed in each telescope, and these reticles are so marked that certain marks are displaced, with respect to each other, the exact amount commensurate with a given range. This is the sole exception to the general rule that in a binocular instrument a reticle is included in one telescope only.

The reticles for stereoscopic range finders are of two general types, depending upon the design of the optical system. Each marking may be indicated with its appropriate range, or a scale

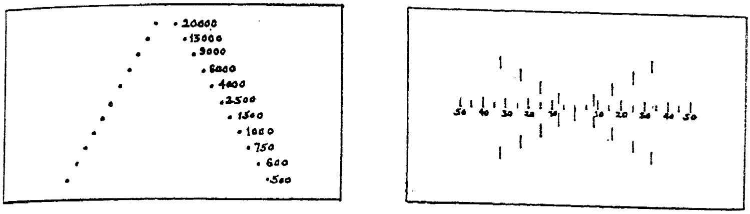


FIG. 185

Reticles of stereoscopic range finder

may be provided at middle distance, and small, unidentified marks indicate depth in front of and behind the principal scale (fig. 185).

312. Measurement of Ranges

Ranges are measured by two methods: 1. By placing the target at the reticle marking which seems to be at the same distance as the target, and reading the range beside the mark. This is for the first type of reticle described above. 2. With the second type of reticle, the target is brought to the center of the field of view, and by means of rotating wedges, brought to middle distance. The range scale is attached to the wedges in the same manner as in the coincidence type range finder. The rotation of the wedges changes the displacement of the object in one field of view with respect to the other, and thus the apparent distance of the object is changed.

313. Measuring Scales

In the smaller range finders, using sliding wedges, the range scale is usually on a revolving drum, and a movable index slides in a helical slot in the drum. Sometimes an optical arrangement is provided so that the range scale may be seen in the field of view or in an auxiliary eyepiece. On the larger types, using rotating wedges, the range scale is usually internal, and is read by means of a microscope (fig. 186).

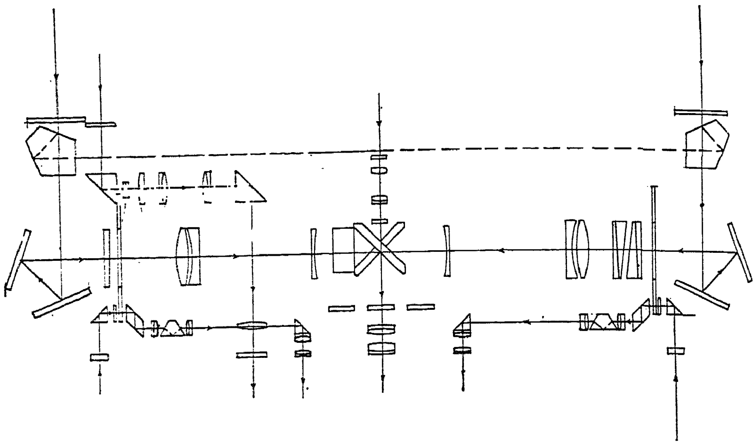


FIG. 186

Optical system of large coincidence type range finder, showing auxiliary optical systems for tracking and scale reading

ADJUSTMENT OF RANGE FINDERS

314. The Infinity Adjustment

The range finder is so delicate an instrument that it is sensitive to changes in temperature and slight shocks from handling. Therefore, it cannot remain in exact adjustment over a period of time, and must be adjusted before each time it is put into use.

The changes in the relationship of the optical elements due to changes in temperature, etc., introduce errors in the form of slight angular deviations in the paths of rays which lead to incorrect range readings and incorrect halving adjustment. Consequently, adjusting mechanisms are provided to make the proper corrections. The halving and coincidence adjustments are in planes perpendicular to each other, the halving adjustment being in a vertical plane and the coincidence adjustment in a horizontal plane.

These errors are independent of range, so adjustment for one range will correct for all ranges. Therefore, the coincidence

adjustment may be made with the fixed wedge, called the *correction wedge,* which, it was stated, is usually adjusted by rotation. This will introduce an error into the halving adjustment if the wedge is single, because of the component of the deviation in the vertical direction.

The halving adjustment is made by shifting the optical bar with respect to the outer tube or by shifting the penta prisms. The shift of the optical bar will shift the lines of sight of the two telescopes in opposite directions.

Since the adjustment for range is most effectively made at infinity, it is usually called the *infinity adjustment.* Adjusting on some object of known range would be the most satisfactory, but is usually difficult to put into practice. Adjustment for infinity may be made upon the moon or a star (if the instrument has astigmatizers). A more common method is the *adjusting lath.* This is a metal lath upon which are marked two vertical lines, at a separation equal to the base length of the instrument. This lath is set up at a distance convenient to the observer (as great as possible) and the two markings brought into coincidence with each other in the field of view. The marks on the lath must be set accurately to a fraction of a millimeter, and the lath must be set parallel to the base line of the instrument within 1°. The latter is usually accomplished by a sighting device on the lath itself and a level. Since individual instruments may vary slightly in base length, each lath must be adjusted accurately to a specific instrument.

315. Internal Adjusting Systems

A much better method of making the infinity adjustment is through an internal adjusting system. This is merely an optical arrangement for producing parallel light entering the two ends of the instrument in beams accurately parallel to each other. The internal adjusting system must be self-compensating, that is, it must produce two parallel beams by *definition,*

else it will be affected by the same sources of error it seeks to compensate.

One type of system consists of two lenses of equal focal length separated by a distance equal to this focal length. Each lens is inscribed with a mark, and thus each lens acts as object for the other, both parallel beams emerging along the optical axis of the system. The marks are illuminated through the edges of the lenses. A small penta prism is mounted in front of each penta prism of the range finder. The penta prism is a constant-deviation prism, thus the beams entering the instrument are parallel within the error of the prisms (fig. 187).

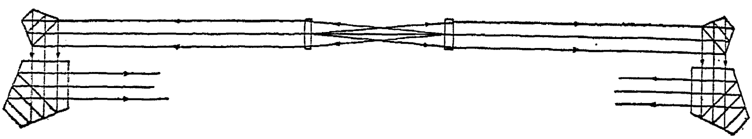


FIG. 187

Internal adjusting system using two lenses

Another type makes use of the principle of the so-called *triple mirror* (88). This prism deviates the light through 180° regardless of its orientation. In this adjusting system, a triple mirror is placed in front of each objective. Thus the light from an illuminated mark in the field of view of the range finder is carried to the opposite objective and into the field of view again, where it is imaged against itself (fig. 188).

Both of the above methods depend for precision upon the accuracy of the deviation of the small prisms, and, furthermore,

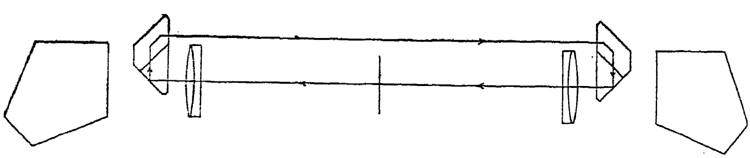


FIG. 188

Internal adjusting system using triple mirrors

the second method will not compensate for any error in the penta prisms of the range finder itself.

Another system, used on most large range finders, avoids both these objections. It also uses two small penta prisms, one in front of each end prism. A small collimator is placed at the side, which, by means of a rhomboidal prism, sends a beam of parallel light into each of the small penta prisms, and thence into each end of the range finder, where coincidence is secured in the field of view. This coincidence may be in error due to lack of parallelism between the collimator and the range finder and due to possible deviation errors in the small penta prisms.

But, if now a second collimator is placed at the opposite end of the system, another reading can be taken by reversing the small penta prisms and this reading will also be in error due to the same causes. But the means of the two errors for each side represents a beam perpendicular to the base of the range finder. Thus, this system represents a completely self-compensating system (fig. 189).

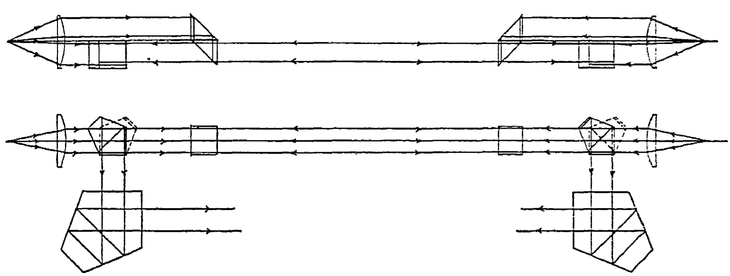


FIG. 189

Internal adjusting system using collimators

316. Accuracy of the Range Finder

The range finder is essentially an instrument for the measurement of angles, and its error can be best expressed in terms of angle. It is empirically known that the average limit of accuracy of the human eye in judging coincidence of two lines

is about 10–15 seconds of arc. Note that this is considerably beyond the resolving power of the eye (412). Adopting 12″ as a mean, and putting M equal to the magnification of the instrument, we see that the minimum angle which can be detected in the field of view of the instrument is 12/M seconds, or 0.00006/M radians. If we put this as dB, then, having found the difference in range for a small change in B from equation (43) as:

$$dr = -\frac{\quad}{b}\,dB$$

we have, for the error in range corresponding to an error dB in B:

$$dr_1 = -0.00006r^2/bM \tag{46}$$

whence we see that the error is proportional to the square of the range, and inversely proportional to the magnifying power of the instrument and its base length.

The extreme range of an instrument would be that distance at which the convergence angle B is equal to the minimum observable value, 0.00006/M, where, from equation (43), we have $r = bM/0.00006$. But at this range, the error dr will be 100%. The extreme range of a range finder is, therefore, determined by the maximum allowable error. Usually range scales are graduated down to the value of r where dr is approximately 10%. For example, the 1-meter base range finder, with a magnifying power of 15X, is graduated to 20,000 yards.

The accuracy of the stereoscopic range finder depends entirely upon the power of stereoscopic perception of the operator. This can be increased through training, and it is found that, especially with the larger range finders, a trained observer with a stereoscopic instrument can make consistently better estimates of range than an observer using a coincidence type instrument. The untrained observer, however, will usually do much better on the coincidence type range finder.

PART III

CONSTRUCTION AND MAINTENANCE OF OPTICAL INSTRUMENTS

CHAPTER XXVII

The Fabrication of Optical Elements

317. Historical

No industrial processes have ever been so shrouded in mysteries as the processes of the optical industry. For two centuries the procedures for the manufacture of optical glass and for the fabrication of lenses and prisms have been passed on by the ancient practice of word of mouth and apprenticeship. In many cases, only a few individuals in a given company were in possession of the details of the procedures, the *tricks of the trade.*

Until the start of the first World War, the optical glassmakers and most of the precision opticians of this country were foreign-born and foreign-trained. The exigencies of war, necessitating the manufacture of many thousands of military optical instruments, led to a thorough program of research and training by military and government departments, and the establishment of schools for the training of optical workers. Then came the establishment of a substantial optical industry in this country, an industry which has expanded prodigiously since 1939. But not at any time have the practices of the optical industry been available in libraries and schools as has information with respect to other industries.

Twenty-five years ago it was a common expression to state that foreign optical instruments, especially German instruments, were superior to any produced in this country. This statement is no longer true. American made optical instruments are the equal of those produced anywhere in the world, although it is perfectly true that American manufacturing

methods often lead to the production of inferior instruments. An optical instrument is a product of extreme skill and painstaking work, and it is not a fit subject for mass production techniques. But if the general average of American optical instruments produced in large quantities is somewhat inferior to foreign products, it is not from any lack of knowledge or skill, merely our unwillingness to sacrifice price for quality.

318. General

The business of producing lenses and prisms is a business of craftsmanship. Optical elements must be finished to tolerances unheard of in mechanical work. An optical surface cannot be considered even moderately good unless it is correct to within a millionth of an inch of its proper form, the roof edges of prisms must be 90° to a tolerance of two seconds of arc. Glass, and especially optical glass, is a very temperamental material; no specific and unalterable methods can be laid down for its fabrication. For these reasons, the optical industry can never adopt the automatic mass-production methods of the mechanical industries.

However, this attitude has been overdone. Optical men have been too certain that their industry was "different"; technological advances which would have been obvious to a mechanical engineer are only now being somewhat grudgingly adopted in optical plants.

Accordingly, much that is written here will be obsolete within a very few years as the optical industry begins to realize that, although it can never be a mass-production industry, in the sense of the mechanical industries, it can, nonetheless, adopt many major improvements in its present methods and techniques.

PREPARATION OF MATERIALS

319. Optical Glass

The manufacture of optical glass is discussed briefly in chapter XXXI. It is furnished to the optical shop in slabs of various sizes and thicknesses, rectangular in shape. The specifications from the designing department will call for lenses of a certain diameter, edge thickness, and radii of curvature, or prisms of specified linear and angular dimensions, to be fabricated from certain definite lots of optical glass.

320. Sample Problem

In order to understand the earlier methods most logically, we will follow a sample lens and prism through the optical shop. Suppose the lens is a cemented achromatic objective with the following specifications: *

Lens I: Borosilicate Crown Glass, Lot 1

$$r_1 = 10''$$

$$r_2 = -5''\text{-diam. } 2'', \text{ E.T.} = 0.10''$$

Lens II: Dense Flint Glass, Lot 2

$$r_3 = -5''$$

$$r_4 = \text{infinity-diam. } 2'', \text{ E.T.} = 0.20''$$

The prism is an Amici roof prism, with dimensions as shown in fig. 190.

Our glass is in square slabs 6″ x 6″ x 2½″ (they might be any size, this is merely a convenient and arbitrary selection). The first job is the preparation of the blanks.

The slabs for the lenses will first be sawed lengthwise into about six pieces, yielding us blanks 6″ x 6″ x 0.34″ approxi-

* These specifications are quite arbitrary, and do not represent a computed lens. Doubtless a lens with curves according to these specifications would be hopeless.

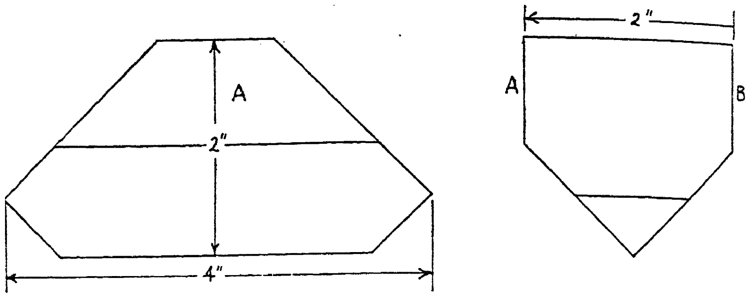


FIG. 190

Design for an Amici roof prism

mately. The flint blanks could be slit into eight sections 6" x 6" x 0.25" approximately. This work is done with a glass saw, a thin brass disk (about 1/32") impregnated with diamond dust or a thin (1/16") abrasive wheel. The cuts are made fairly rapidly, the glass being cooled by a stream of water, but not as rapidly as wood or metal might be cut. The slabs are then cut into four equal parts, yielding us blanks for the crown elements 3" x 3" x 0.34" and for the flint elements, 3" x 3" x 0.25".

For the prisms, the slabs are cut into blocks about 4¼" x 2¼" x 2¼". This will waste some glass, but there is no way in which we can get more than two prisms out of a slab.

The lens blanks are now nipped or sawed into approximately circular form and then ground down to diameter. The rough blanks are stacked into a column of twenty or more, stuck together with pitch, shellac, or other binder, mounted between two wooden blocks on a horizontal spindle, and held against a wide abrasive wheel. The diameter is ground down to about 2⅛", to permit centering later.

The next process, with respect to both lens and prism blanks, is to grind one side flat by holding each blank individually against a large flat iron disk about 24" or more in diameter, using a coarse abrasive (60 or 80 mesh) and water. We now

take a large iron plate, about 12″ in diameter (sizes of grinding disks depend entirely upon the equipment available in the shop) and place our disks upon it, ground side down. The iron plate has been carefully machined flat, then ground against a master plate until its surface is as flat as it can reasonably be made. The disks are set in paraffin or shellac or other binder. The block of disks is then ground on the big grinding plate with the coarse abrasive, moving the block back and forth with the help of a pivoted arm. The lens blanks are ground until a micrometer measurement shows them to be about 0.30″ and 0.22″ thick for crown and flint, respectively. To facilitate this micrometer measurement, the disks mounted near the edge of the block have been allowed to overlap the edge by about ⅛″.

In grinding the original flat surface of the prisms, we select side A as shown in fig. 190 and we mount these on the block in the same way as the lens blanks, and grind down side B until the thickness is 2.0″. These two sides are not to be polished, so they can be ground down immediately to final dimensions.

The preparation stage is now complete. If we were to produce a great many of these units, we might have prepared the blanks by *pressing*. The slabs would have been cut into sections of the proper *weight*, then placed in molds and put in a furnace until soft, then pressed into the molds and allowed to anneal. The molds might even be made with curved sides for the lens blanks, so that the finished blanks would require a minimum of grinding in the shop. This procedure would not, however, be practicable for a small quantity. Only the larger optical shops have pressing plants, although for the production of military instruments during the war, most of the glassmakers have installed pressing plants and furnish the blanks to the optical shops already prepared for grinding.

GRINDING AND POLISHING

321. Rough-Grinding Lenses

The next step is to grind one of the convex surfaces of the crown element and the concave surface of the flint. For this purpose, the machine shop has prepared a sufficient number of convex and concave cast-iron tools of 5″ radius. These tools have been accurately turned and then ground carefully against master tools until the radius is correct to within about 0.01″ and the sphericity within about 0.00001″ as indicated by a glass test plate (333, fig. 191).

FIG. 191

Interference fringes as seen under test plate

The grinding is done with a slightly finer abrasive and the blanks may be held in the hands or mounted on a wooden handle as the operator prefers. If the lenses were small and of gentle curvature, we might mount several of them together on a wooden or metal block with pitch for this grinding process. In our case, we would most likely choose to do them individually (fig. 192).

When one side is completely ground, the blank is turned over and the other side ground. In the case of the crown, the other radius is 10″ and we have special tools for this surface. This radius being somewhat longer, we will doubtless mount about

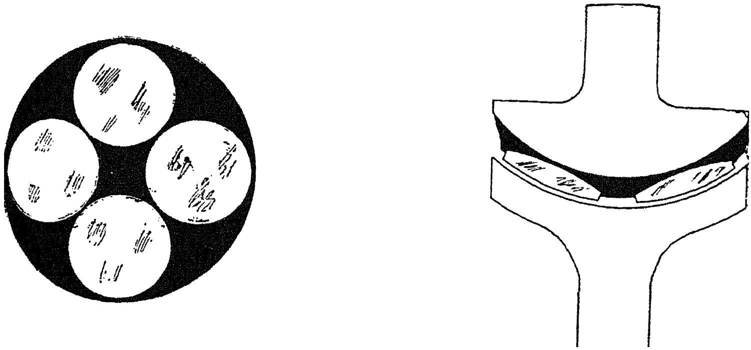


FIG. 192

Lenses blocked for grinding

five blanks on a block. The block is metal and has a radius (convex) of about 10½″. Each lens blank receives a "button" of warm pitch by means of which it is attached to the block. Before the pitch has set, the block with lenses attached is set into the grinding tool and pressed with a heavy weight until the pitch has set and the blanks are firmly in place. The grinding then proceeds as for the first surface.

In the case of the flint elements, the reverse side is flat, and it has already been ground flat from the previous operation. Therefore, there is no further rough grinding to be done on this element.

During the grinding of the second surface, the blanks are frequently checked for thickness, and grinding proceeds until the edge thickness is about 0.12″. In the case of the flint, this checking of thickness had to be done while the first side was being ground, and it was the center thickness which was checked, since the edge thickness has not changed.

322. Abrasives

There are many kinds of abrasives used in the grinding of optical elements. Carborundum (silicon carbide) is the

most popular. It is produced under other trade names. It is used in granular form, 80–100 mesh being the usual grade for rough grinding. Other abrasives are the aluminae, alundum, aloxite, etc., and emery, the latter being most usually used for fine grinding. These are all aluminum oxide (Al_2O_3) in different crystalline forms. Boron carbide is a much harder abrasive, which works much faster, but is considerably more expensive. Steel filings have even been used for rough grinding, but these break down rapidly. Diamond dust would be a superb material, but far too expensive for such general use. The action of the abrasive is to chip away the glass, forming a surface of pits of a depth which depends upon the size of the abrasive grains.

323. Grinding Prisms

Our prism surfaces are, of course, flat, which simplifies the problem somewhat; but prisms require a special method of blocking. The usual custom is to prepare a metal block milled accurately with grooves to hold the prisms in the proper position for grinding. The prisms are laid in the grooves and bound in place with paraffin or shellac. One side after another of our prisms is ground, the angles being carefully checked with precision angle gages after each operation. The dimensions are left about 0.01″ oversize to allow for fine grinding and polishing (fig. 193).

324. Fine Grinding

The fine grinding procedure for both lenses and prisms is the same as for rough grinding, except for the grade of abrasive used. Several different abrasives may be used in fine grinding, successively finer as the work proceeds. The finer the final grade, the shorter will be the necessary polishing time.

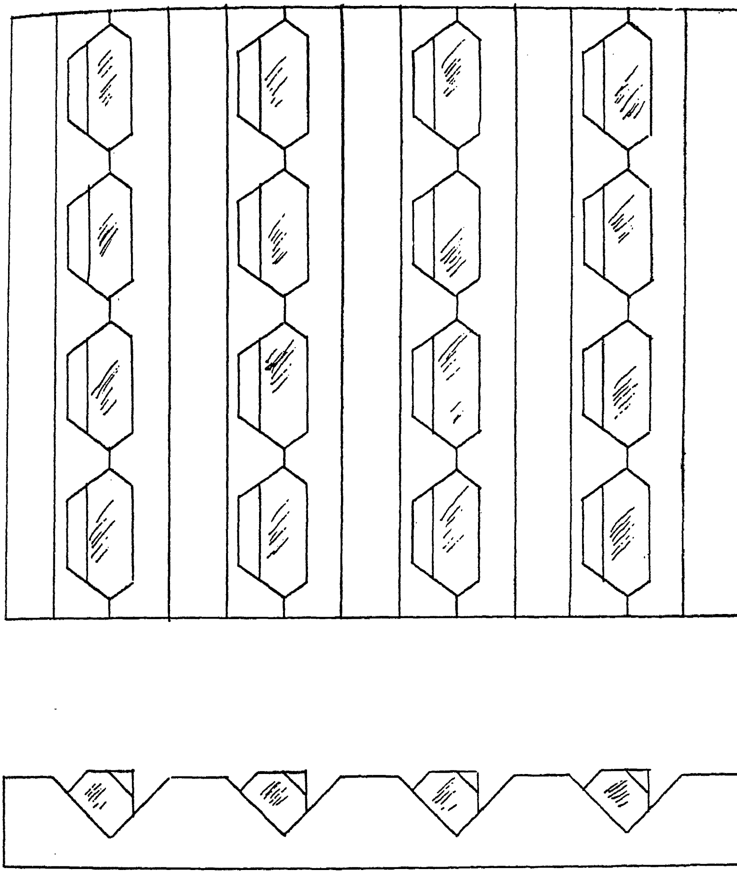


FIG. 193

Prisms mounted in V-block for grinding

325. Grinding Wheels

The optical industry has recently discovered that glass can be successfully ground on machines using high-speed grinding wheels similar to those used on mechanical surfaces. This has been especially true of the flat surfaces of prisms. This grinding is very rapid, the surface produced can be polished

directly, eliminating the fine grinding operation, and dimensions can be controlled very accurately.

Even more recently, methods have been devised for the grinding of convex and concave surfaces by similar methods, using diamond wheels, in which the wear is negligible. The wheel is cup-shaped, and the machines are known as *curve generators.*

326. Polishing

For polishing our lenses, the machine shop has had to furnish new sets of tools. These tools are to be covered with a layer of pitch, resin, wax, cloth, or paper, depending upon the type of work and the shop foreman, and their radii are, therefore, cut accordingly. Since the metal surface does not do the polishing work, the radii and the sphericity do not need to be held to such close tolerances. Pitch polishers are used almost exclusively for precision work. Cloth and paper polishers find favor with the manufacturers of spectacle lenses.

Lenses are always blocked in pitch for polishing. The radii of the surfaces will control the number of lenses that it is possible to mount in one block, and will likewise control the size of the tools which can be used (fig. 194, 195).

Otherwise, the procedure for polishing is the same as for grinding, but the operation will be much more lengthy. The abrasives used are known as rouge, common or "red" rouge being ferric oxide. Other polishing agents, such as ferric ferrous oxide, tin oxide, chromic oxide, manganese dioxide, cerium oxide, etc., are also known as rouge, although they may not be red.

It is common practice to fine-grind and polish a surface without reblocking the lenses or prisms. This saves considerable time. When one side has been fine-ground and polished, it is coated with shellac or lacquer to protect it during the fine-grinding of the opposite side.

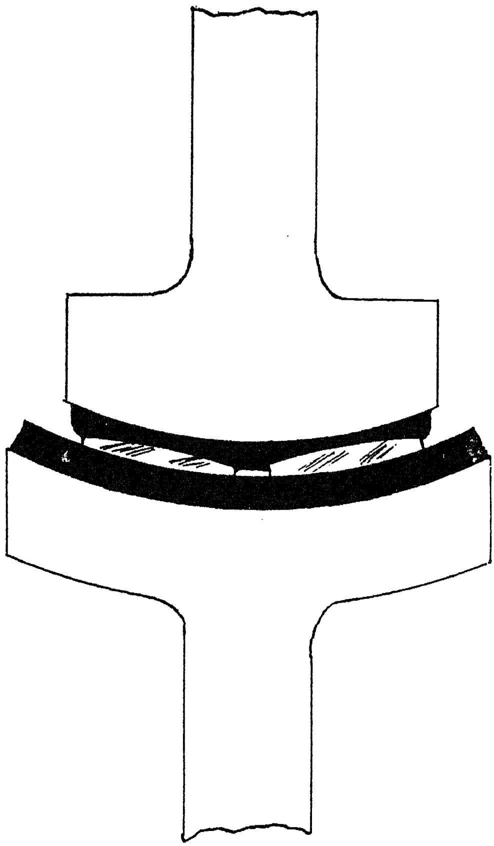


FIG. 194

Crown lenses blocked for polishing

327. Blocking Prisms for Polishing

Usually the metal *V-blocks* used for grinding prisms are not of sufficient accuracy to permit their use in the polishing operation. The face of the prism to be polished is placed upon a flat metal disk which has been accurately ground to flatness, probably to 0.00001″. A thin layer of wax is poured around the

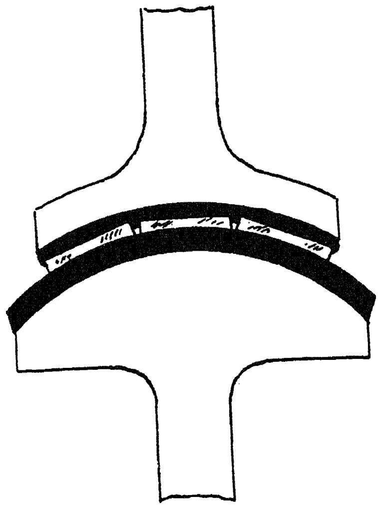


FIG. 195

Flint lenses blocked for polishing

prisms to protect the master plate, and then plaster of Paris is poured in of sufficient depth to cover the prisms. A metal plate is attached to the back of this block, and when the plaster has set, the block is turned over and the plaster chipped away from the exposed faces of the prisms to a depth of about 1/16″ to avoid contact between the polisher and the plaster (fig. 196).

When one surface has been polished, the blocking may be performed on an optical flat, in which case the surfaces are so closely matched that air pressure will hold the element firmly in position. This method of blocking is known as *optical contacting*, and is not frequently used, since optical flats of large size are very expensive, and damage to the surface is rather common when used for blocking. Another method involves the use of a *fence*, a block of optical glass with accurately square shoulders. Prisms containing a 90° polished angle (particularly roof prisms) are optically contacted along the sides, and the entire surface, including fence and prism, polished down (fig. 197).

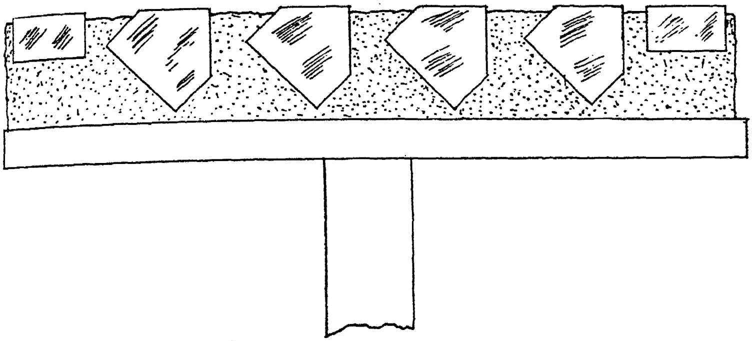


FIG. 196

Prisms blocked in plaster for polishing

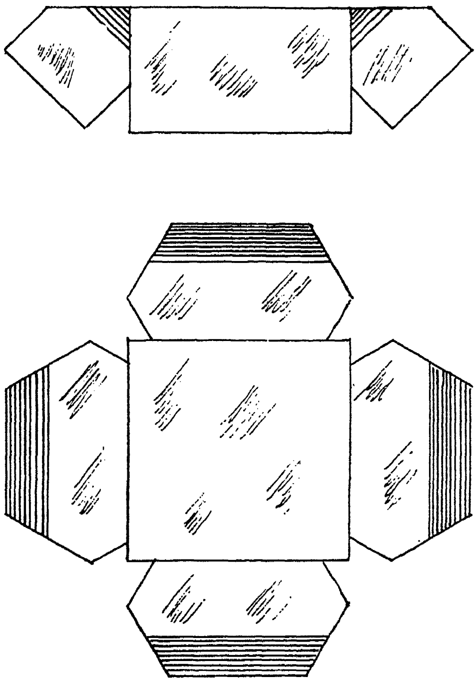


FIG. 197

Prisms mounted on "fence" for polishing

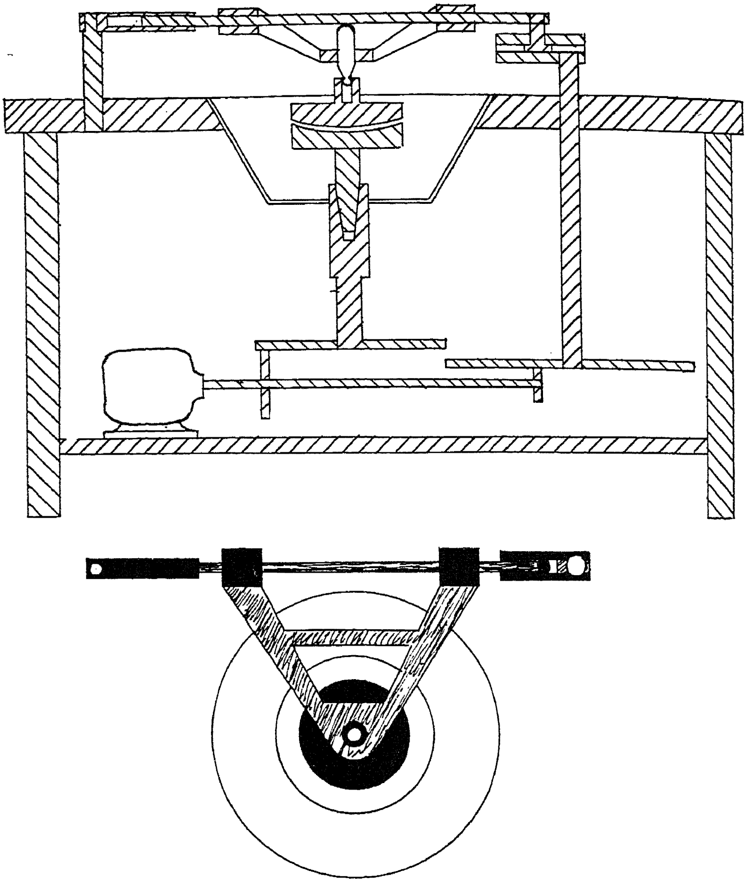


FIG. 198

Schematic diagram of optical grinding and polishing machine

328. Grinding and Polishing Machines

The optical grinding and polishing machine is a simple affair. A vertical spindle holds the block of lenses or prisms and is rotated by a motor at a slow speed (100–500 RPM). The tool is held over the block by an arm which is actuated

by a reciprocal drive, giving the tool a back-and-forth or an elliptical motion. The tool is always set off-center of the block, so that friction against the elements causes the tool to revolve also, at a somewhat lesser velocity. The arm actuating the tool is adjustable to give different lengths or forms of *stroke* (fig. 198). The abrasive is fed by hand or pumped through a tube for continuous flow. Tool and block are interchangeable in the machine. It is customary to mount the convex one on the spindle, and the concave on the arm. The tools and blocks may be any convenient diameter, depending upon the available power of the machine, but cannot have a diameter greater than twice the radius of the surface being worked upon.

329. Centering

When the lenses have been completely polished on both sides the next operation is *centering*. This is a process of grinding down the diameter of the lens until it is concentric with its optical axis. The optical axis is determined by the position of the two centers of curvature (56).

The lens is pitched or shellacked onto a horizontal spindle and adjusted until the images of a convenient object reflected in the two surfaces, or a pinhole or slit seen through the lens, remain stationary when the spindle is rotated. The pitch is allowed to set and then the spindle is shifted until the lens rests against a grinding wheel. The operation continues until the lens has been ground circular and to the proper diameter. This is termed *edging* or *centering*. Edging machines are semiautomatic, being provided with stops which prevent the lens from advancing into the wheel after the proper diameter has been reached.

330. Figuring

In the case of lenses of large diameter, slight variations in the index of refraction of the glass and the inevitable tiny error introduced by variations in the radii of curvature between the

actual lens and the exact specifications laid down by the designer may make it necessary to do hand *figuring*. This is a process of polishing (or grinding) by hand, usually in definite local areas, resulting in a change in the curvature from the spherical form produced by the grinding and polishing machine. In the case of parabolic telescope mirrors, the surface is ground and polished spherical and then turned into a paraboloid by figuring.

In the case of prisms, a similar procedure is used when the tolerances of the prism are too small to be achieved by machine polishing. For roof prisms, the 90° angle must be almost perfect, and it is necessary to check this angle with a sensitive gage all through the stages of grinding and polishing. The angle cannot usually be held within the tolerance by polishing technique, so it is necessary to make a final correction by hand. A *performance* test determines the accuracy of the roof angle. If not correct, one side of the roof is polished against a very hard pitch lap by hand until the angle is adjusted to $90° \pm 2''$. Tolerances on other prisms and on the other angles of roof prisms are usually of the order of $5'$–$15'$, well within the possibility of holding through machine polishing on large blocks of prisms.

331. Pitch

The pitch used for blocking and for polishing laps is one of the most temperamental of materials. It is an amorphous material in which the particles of rouge become embedded and thus it has the effect of cushioning its effect upon the glass. It flows under heat and pressure and readily assumes the exact shape of the surface being polished. The base is usually pine pitch, or resin, or refined asphalt, and it frequently contains quantities of resin, beeswax, paraffin, mineral oil, soap, etc., when mixed in the optical shop. Its change in viscosity with temperature is very similar to that of glass, except that the effective range of temperature is much smaller and in

lower parts of the scale. At room temperature it is usually quite hard, although it will deform slowly and smoothly under pressure. As the temperature rises, it becomes soft, being quite pliable at about 150–200° F. At its critical temperature, or melting point, about 200–300° F, it loses almost all its viscosity very rapidly, and becomes a thin liquid.

Its viscosity at the working temperature of a polishing lap may be varied between rather wide limits by slight changes in the ingredients, and the formula used will depend upon the room temperature, the material to be polished, the kind of polish desired, and the individual preferences of the operator.

332. Cementing

Our lenses have been polished on both sides, edged to the correct diameter, and are now ready to be cemented together into an achromatic objective. The material used is Canada balsam, a product obtained from coniferous trees. It is transparent and colorless and has an index of refraction very nearly that of crown glass.

If the balsam is obtained in liquid form, it must be prepared by heating it to drive off certain volatile components. This preparation may be made at the time of cementing the lenses, or it may have been done previously, and the balsam prepared in *stick* form.

The lenses are thoroughly cleaned and heated to about 250° F, at which temperature the balsam melts to a thin liquid, and is applied over the entire area of the surface to be cemented. The two components are then placed together, all bubbles in the balsam squeezed out, and then the elements are pressed together until the layer of balsam is as thin as possible. The lenses are then placed in V-blocks to hold them centered and the cement allowed to set. Lenses may easily be decemented by heating on a hot plate to about 200–300° F. The Canada balsam becomes soft and the elements are easily separated. The cement may then be dissolved with alcohol or other solvent.

Due to the tendency of Canada balsam to crystallize under high and low temperatures, other materials, notably the methacrylate plastics, have been used in the cementing of lenses intended for military use. These cements are thermo-setting, so cannot be remelted by the application of heat. Decementing of these new materials is done by "shock." The cemented lens, at room temperature, is plunged into oil at a temperature of about 400–450° F., whereupon the difference in rate of expansion between crown and flint components breaks the seal. Breakage is not infrequent from such heroic treatment, although it can be kept within 10%. An alternative method is to heat the lens to about 250° F. and then plunge it into cold alcohol. This method seems to give a higher rate of breakage.

After, or during cementing, the lens is tested for concentricity in a *collimator.* The lens is held in a chuck, and forms an image of a suitable reticle, which is observed through a telescope. The chuck is rotated, and any shift of the reticle image observed.

333. Testing of Optical Elements

As the lens or prism progresses through the shop, certain inspections must be made at each stage of the process to determine whether the finished element will be in accordance with specifications. It is assumed that the original blank was checked for bubbles, stones, striae, strains, etc., before being put into process. Up to the polishing stage, the only ascertainable facts are the character of the surface and its dimensions. Chipped or broken elements are, of course, easily distinguished. Dimensions (diameter and thickness) are checked by micrometers. The radii of curvature are checked from time to time with a spherometer (fig. 199) to determine whether the grinding tools need correction. For every grinding tool there must be a master of opposite curvature, and from time to time the tool must be ground against the master, since it will wear unevenly and its radius of curvature will change. Flat tools

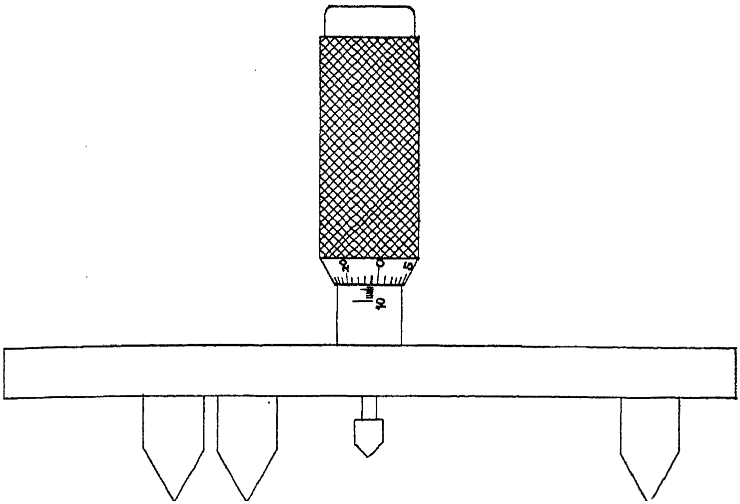


FIG. 199

A simple type of spherometer

are not quite as subject to uneven wear as spherical tools, but they also must be reground at frequent intervals.

The degree of perfection of a polished surface is determined by examination with a magnifier. The degree by which it conforms to its proper *shape* cannot be judged by direct examination, but requires an optical test. The most common method is by the use of a test plate.

A test plate is a piece of optical glass carefully ground and polished by hand to the correct radius. Its curvature is opposite to that required on the lens. The test plate is placed in contact with the lens (which need not be removed from the polishing block) and the pattern of interference fringes (chapter XXXIII) is studied. These fringes (Newton's rings) can be considered as contour lines, indicating the relative shape of tool and test plate. Each fringe denotes a difference of half a wave-length or about 0.00001″. If the fringes are circular (straight in the case of a flat surface) then the lens is spherical.

The number of rings visible indicate the variation in the radius of curvature. Even a difference in curvature sufficient to show a dozen or more rings may not be sufficient to place the lens beyond focal length tolerance. The principal purpose of this test is to determine whether the surface has the proper *shape,* so if the rings are not circular, but irregular, the lens is rejected and repolished.

The angles of finished prisms are checked with a spectrometer as described in (242). When a large number of prisms are to be checked in this way, the spectrometer may be simplified considerably to measure deviations from a given angle, but the principle is similar. The 90° roof prism angles are customarily checked by a *performance* test. The prism is placed in front of the objective of a small telescope and a suitable target is examined through the prism. Any variation in the roof angle from the required 90° will give a doubling of the image. If the target is properly made, the size of the markings will determine whether or not the prism is beyond the specified tolerance.

Complete lenses are best checked with respect to focal length, definition, and aberrations by examining under a microscope the image formed by the lens of a star (real or artificial). Various special tests have been devised to test for specific aberrations, such as spherical aberration, and for the testing of aspheric surfaces, such as paraboloidal telescope mirrors and Schmidt camera correcting plates.

In making an examination of a point image formed by a lens, it should be formed with the object at the same distance as it would be in the application of the lens to an instrument, since, as explained in (120), a lens may be perfectly corrected for one object position and yet show very large aberrations for a point at a different distance.

MIRRORED SURFACES

334. Application

It is frequently found necessary to coat surfaces of optical elements with reflective coatings. All mirrors must, of course, be so coated, and reflecting prisms where any of the rays to be reflected are not safely above the critical angle (28), for example, penta prisms, must also be coated.

335. Silvering

Chemically deposited silver is the most familiar of reflective coatings. It is deposited by chemical action out of a solution of a silver salt. (For processes of silvering, see chapter XXVIII). Silver coatings are soft and easily damaged and are especially subject to tarnish from exposure to air. Therefore, they are satisfactory only if the reflection is to take place from inside the glass. In this case, the exposed surface can be protected, usually by copper plating and painting.

For optical purposes, mirrors coated on the back are not very satisfactory, because a certain amount of the light is reflected from the front surface, causing multiple images. For this reason, prisms are frequently used in places where mirrors would otherwise have been preferable (127).

336. Metallic Vapor Deposits

It is now possible to make front-surfaced mirrors by vaporization of metals, principally aluminum. A small quantity of the pure metal is placed on a tungsten filament in a high vacuum chamber. A heavy current is sent through the filament, the metal vaporizes and deposits a thin, even coating over the sides of the chamber and any articles contained in it. These coatings do not tarnish, as the oxidation product is colorless in a thin film. Moreover, the aluminum oxide is very hard and forms a protective coat over the metal. Certain other

metals have occasionally been used for this purpose, and some metals, notably chromium, have been alloyed with aluminum in coatings.

337. Anti-Reflection Coatings

In 1892, H. D. Taylor, in England, made the somewhat startling discovery that certain old photographic lenses which had become stained and tarnished were actually faster, i.e., admitted more light, than new, unblemished lenses. This could not be due to any absorption inside the glass, but must be due to a reduction in the loss from reflection at the various glass-air surfaces. For many years, methods were sought for treating the surfaces of lenses by a chemical or mechanical means to reduce reflections, without notable success. In recent years, the vacuum deposition process has made possible the coating of lenses with various materials, usually metallic fluorides, so as to reduce reflections to the point where the light actually transmitted through an instrument is increased by 25% or more.

The answer to this seemingly paradoxical situation lies in the interference of light (chapter XXXIII). The thin transparent coatings are a quarter of a wave-length thick, so that the light reflected from the inside of the coating is exactly 180° out of phase with the light reflected from the outside of the film, and destructive interference occurs. Now, energy cannot be thus destroyed, and the energy cancelled out reappears in the transmitted beam, in the same way that the maxima of spectra become brighter as the minima become darker.

An additional necessary condition is that the index of refraction of the coating material is less than the index of refraction of the glass. Strictly, its index should be the square root of that of the glass. Substances with such low indices are unknown, but the metallic fluorides have indices (about 1.38) which approach the requirement nearly enough to give high efficiency. Skeletal structures in the film have been

produced with certain materials which have an *effective* index of the required value, but such films are not at all durable.

The principal difficulty attending this process has been the production of coatings which are sufficiently durable to withstand weather conditions and cleaning operations. This has been overcome by improvements in technique, and coatings produced at the present time are nearly as hard as the glass

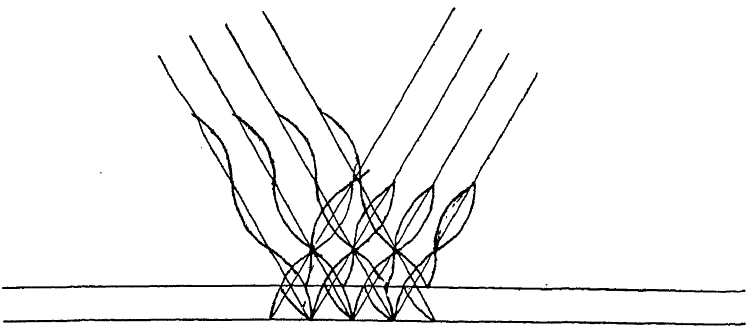


FIG. 200

Interference of reflected light by anti-reflection coating

itself. The thickness of the coatings is usually about a quarter the wave-length of yellow light, thus yellow and green light are almost completely transmitted. As a result, the coated lenses, when examined by reflected light, have a decidedly purple tinge, and may be thus recognized (fig. 200).

338. New Optical Materials

New optical materials developed as a result of the present war will result in major changes in the industry after the war. After much research and experiment, the methacrylate plastics (synthetic resins) have been rendered satisfactory for use as the material of lenses and prisms. Even achromatic lenses of plastics are possible. These materials offer many possibilities for the manufacture of optical elements without the tedious

and expensive procedures of grinding and polishing, necessary with glass.

They do not offer anything new in the way of optical properties, however, in fact, the designs possible with plastics are somewhat limited and it is doubtful if they will be satisfactory for anything but low-power commercial instruments. Certain other materials do, however, offer special optical properties, and the cessation of the war should see many important advances due to their use.

CHAPTER XXVIII

CARE AND CLEANING OF OPTICAL ELEMENTS

339. Durability of Optical Glass

Glass has always been a material much misunderstood by the laity. It is frequently thought of as an extremely hard, practically impervious material, rather brittle, but otherwise unaffected by chemical or mechanical agents. Considering glass in the bulk, this opinion is more or less justified, but considering an optical surface on glass, polished to a degree of smoothness and accuracy which cannot be measured by any mechanical means, one discovers a host of chemical and mechanical agents which have a very deleterious effect upon glass. Moreover, many of the resistant properties of commercial glass have to be sacrificed to attain the more necessary properties of transparency, homogeneity, and chemical stability necessary in optical glass, and it is, as a result, much softer and less resistant than the glass used in cooking utensils and insulators.

340. Care of Optical Elements

Since optical glass is subject to corrosion by moisture and by many agents found in dust and grease, optical elements should be kept clean and dry at all times. It is obvious that optical elements should be protected from damage by breakage, perhaps not quite so obvious that ordinary dust contains gritty particles which will scratch the highly finished surfaces if it is rubbed when dry, even with the softest of materials. Optical surfaces should never be touched with the finger if avoidable; perspiration contains a substance which corrodes glass.

341. Cleaning of Optical Elements

Optical instruments should be disassembled and the optical elements cleaned rather frequently. Cleaning lenses and prisms is not a difficult or a lengthy task, but very great care must be exercised that the surfaces are not scratched or damaged in the process.

Before optical surfaces are subjected to any cleaning process, they should always be dusted thoroughly with a soft brush and with an air bulb, to remove any dust particles which might be rubbed into the surface during the cleaning process. A vacuum hose is excellent for removing dust particles which have been loosened by brushing, as dust particles stick quite securely in the oily film formed on a glass surface which has been exposed to air. An air-pressure nozzle should never be used to clean optical surfaces unless the air is thoroughly filtered.

342. Mechanical Cleaning Methods

Cleaning of optical surfaces by mechanical means should be avoided so far as possible. Any sort of mechanical action is likely to be too severe for the delicate surfaces. Occasionally, however, foreign material is so firmly attached to the surface that it must be removed by mechanical means. Rouge, etc., may be removed from the *ground* edges and faces with a fine abrasive, but there is considerable danger of damaging the polished surfaces and the method is not recommended.

Finely ground materials softer than optical glass, such as magnesium carbonate, magnesium oxide, calcium carbonate, silica, etc., are sometimes used to remove persistent stains, fungus growths, etc. *Rouge should never be used as a cleaning agent.* If these materials are used, care must be taken to see that they do not contain any hard foreign particles.

343. Cleaning Solvents

Probably the safest method of cleaning optical surfaces is by the use of a suitable solvent. The nature of the material to be removed must be considered in choosing the proper solvent.

Although soap is not a solvent in the strictest sense of the word, we will mention it at this point. A weak soap solution (5–10%) is widely used in general optical cleaning, and it will remove most ordinary foreign substances. It is advisable, however, to use a soap whose metallic salts are water-soluble, else there is a danger of leaving an insoluble patina on the surface. *Detergents,* which appear like, but are technically different from soaps, are of great efficiency in cleaning optical elements. They evaporate readily, without leaving a film behind, and are quite satisfactory for ordinary cleaning without additional treatment. They are sold under various trade names, such as Aerosol, Orvus, Dreft, etc. If the surface can be thoroughly cleaned by merely flushing with soap solution, it is well to do the cleaning in this way. If necessary, the surface may be *gently* rubbed with a very soft cloth or chamois. Cloth used on optical surfaces must be lint-free. Commercial absorbent cotton usually contains small gritty particles and is to be avoided.

Various types of organic and inorganic solvents are available for cleaning optical surfaces. The solvent used will depend, of course, on the nature of the material to be removed from the surface. Gasoline, naphtha, xylol, toluol, benzol may be mentioned, and are especially valuable in removing pitch, resin, paraffin, etc. Shellac and beeswax may be removed with alcohol. Acetone, ethyl acetate, methyl ethyl ketone are useful in removing lacquer coatings, etc.

One of the most efficient methods of cleaning is by the use of hot trichloroethylene. The solvent is used at its boiling

point of 188° F. Trichloroethylene is inflammable, so its use requires special equipment and extra precautions.

Acids and alkalies, especially alkalies, are to be sedulously avoided, because of their probable corroding and leaching effect upon the surfaces. Soap solutions containing ammonia, for example, should not be used.

344. The Use of Solvents

Soap solution, gasoline, and alcohol are the more likely solvents to be available to the casual user. The use of soap solution has been discussed. In the case of gasoline or alcohol, the elements are placed in a shallow pan of solvent, covered with a glass plate (to prevent evaporation and entrance of further dust) and soaked for several hours. They are then removed, washed in fresh solvent, and dried with a clean, soft cloth, chamois or other suitable material. Paper tissues are sold for the purpose of optical cleaning. Some of these are good, others contain hard particles. If good, they have the distinct advantage of being disposable.

In using any solvent, the properties of the solvent should be carefully investigated. The solvent may be inflammable or toxic, and due precautions must be taken in its use if this is true.

345. Cleaning Cemented Lenses and Prisms

Cemented lenses should never be soaked in a solvent unless it is definitely known that the cementing material (usually Canada balsam) is insoluble in the particular solvent being used. *Canada balsam is soluble in nearly all ordinary solvents.* If cemented elements are to be cleaned by solvents, the solvent must be applied to the surface with a pad of cloth or tissue, which may be wrapped about the end of a pencil or wooden stick.

346. Cleaning Burnished Lenses

When lenses are burnished into their cells it is impracticable to remove them for cleaning. Cleaning must be done with a padded stick, as described in (345). The lenses are frequently also sealed in, and in all likelihood the sealing compound will be soluble in the solvent being used, and extreme care must be taken not to smear this compound over the lens while cleaning it.

347. Cleaning Front-Surfaced Mirrors

In the cleaning of front-surfaced mirrors, extra care must be taken to avoid scratching, and the possible action of a solvent upon such a surface must be investigated thoroughly. It is safer to use the soap solution, and clean exclusively by flushing, wherever possible.

348. Coated Surfaces

Modern surfaces coated for anti-reflection qualities require no special considerations, with respect to *mechanical* actions in cleaning. The possible effect of solvents upon the particular material with which the lens is coated must, however, be taken into consideration. Soap solution is usually safe on any surface. Earlier efforts at producing anti-reflection coatings resulted in rather soft surfaces, to which the methods of cleaning front-surfaced mirrors apply.

349. Silvering

Mirrored surfaces frequently become scratched, tarnished, or otherwise damaged without harm to the glass. In these cases, resilvering will restore the utility of the mirror. We refer, of course, to back-surfaced, silvered mirrors. Elaborate and expensive equipment is necessary for the application of vacuum deposited metallic coatings on front-surfaced mirrors. The only equipment necessary for silvering is a supply of glass

bottles for chemicals and solutions, tongs or rubber gloves, and shallow glass trays for the silvering process. The chemicals required are: nitric acid, distilled water, cane sugar, silver nitrate, potassium hydroxide, and ammonium hydroxide. In addition, a supply of absorbent cotton will be necessary.

Two solutions are prepared. The reducing solution consists of 4.75 oz. cane sugar to 6 cc. nitric acid and 1 liter distilled water, boiled for 20 min., then cooled to room temperature. If stored for a length of time, add 50 cc. grain alcohol before storing. Keep in a glass container. The silvering solution consists of 10 gm. silver nitrate, 100 cc. distilled water, 5 gm. potassium hydroxide, 15 cc. ammonium hydroxide, and a quantity of a weak solution of silver nitrate in distilled water. The silver nitrate is dissolved in the distilled water, then the potassium hydroxide added, and the mixture stirred until a precipitate forms. Ammonium hydroxide is then added until the precipitate clears. Silver nitrate solution is then added until the mixture is a light straw color.

Before silvering, a surface must be absolutely clean. Nitric acid is used for cleaning, swabbed on with cotton. The surface is then rinsed with distilled water. A test of its cleanliness is that the water will flow evenly over the surface and not form into globules. All traces of the nitric acid must be removed.

The silvering bath is prepared by adding one part of the reducing solution to two parts of the silvering solution in a shallow glass tray, filling it sufficiently deep to cover completely the surface to be silvered. The surface is placed in the bath, face up, using tongs or the hands encased in rubber gloves. Opinion differs whether the surface should be agitated during the deposition of silver or whether it should be kept perfectly still. When the bath has turned gray and small flakes of precipitated silver appear on the surface, the process is complete. The surface is removed and rinsed in distilled water.

All portions of the surface and sides of the element will be coated with silver. To remove the silver coat from surfaces

not intended to be silvered, stick adhesive paper or tape over them carefully, and then peel it off. The silver coat will come off on the paper. Any lingering spots may be taken off with a small swab dipped in nitric acid.

The completed silver coat should be covered with a copper plate (electrolytic) or paint, or both. It is perhaps superfluous to warn against touching the surface with the fingers at any time, and to remind that nitric acid will cause severe burns.

The above process is only one of many silvering processes, and there are numerous other and perhaps better ones. The one above, however, is simple and gives good results if the directions are carefully followed. If it is desired to slow down the deposition of the silver coat to produce perhaps a partially-silvered surface, a little honey added to the solution will decrease the rate of precipitation of silver.

CHAPTER XXIX

Optical Adjustments

350. Adjustment of Instruments

No general rules can be laid down for the adjustment of instruments, since there are as many kinds and means of adjustment as there are instruments. Considerable thought is sometimes necessary to develop an effective means of testing for various maladjustments, and these problems must often be solved for the particular case.

In these two chapters, various common maladjustments are mentioned and described. There are others which may apply to specific instruments. The common means of adjustment are indicated, but any individual instrument may be provided with a different means. An important thing to remember is that the adjustment for one feature may involve others as well, and thus must be carefully considered before an adjustment is made. For example, the adjustment of binoculars for tilt will probably destroy collimation, so adjustment for tilt should be performed first, and care taken that it is not vilified later when the instrument is collimated. Common features for which adjustment must be made and which we shall consider here are:

Collimation	Parallax
Double Vision	Horizontal and Vertical Travel
Focusing movement	Line of Sight
Tilt or Lean	Backlash and Endplay
Definition and Resolution	Level Vials
Diopter Scales	

Those of the above which involve mechanical adjustment will be covered in chapter XXX.

In the adjustment of an optical instrument, there is no substitute for a thorough understanding of the instrument's operation and optical theory. If this is lacking, the individual can do nothing more than go through a set of stereotyped movements without any clear idea of what he is trying to do. When it is necessary to develop a technique of testing and adjusting, the individual must understand the principles of the optical system he is working with and the effect of the operations he is performing.

351. Precautions

Whenever an optical instrument is disassembled for cleaning and/or adjustment, several precautions must be rigorously observed. Before any parts are removed, scribed marks should be made, showing the original position of the parts, so that they may be reassembled in *exactly* the same positions. All lenses removed from cells should be marked on the ground edge with indelible pencil (not soluble in the solvent being used for cleaning) showing in which direction they should be placed in the cell. If several apparently identical prisms are found in an instrument, each must be returned to its original position, or it may be impossible to adjust the instrument upon reassembly. Porro prisms in binoculars, for example, are carefully matched as to size and deviation in pairs, and must be returned to the identical locations from which they were removed.

Almost all cells and retaining rings in optical instruments are locked in place with small radial set screws, which *must be removed before the cell or retaining ring can be removed.* These set screws may be covered with sealing compound or paint, and their heads may be filed off. Always be absolutely certain that set screws are taken off before attempting to remove a cell or retaining ring. If the parts do not unscrew

easily, the reason is probably a set screw, and if this is not removed, the part will be damaged beyond repair.

352. Collimation

Collimation refers to alignment. In collimating an optical instrument, its optical parts must be aligned in the manner in which they were designed to be aligned. The optical axes of all lenses should coincide with one another, and the surfaces of prisms should be set at the proper angle (usually 90°) with the optical axis. The accuracy to which collimation must be carried depends upon the purpose for which the instrument is to be used. In an astronomical telescope, for example, the slightest "cocking" of the objective will be noticeable in the diminished quality of the images. In a telescope for ordinary terrestrial use, however, a considerable maladjustment may be undetectable.

Nearly all optical instruments in which proper collimation is an essential factor have their optical elements mounted in such a way as to provide for small adjustment in transverse position. In large telescopes for example, the objective cells are carried on push-pull screws (152). In small terrestrial telescopes, however, it is usually considered sufficient to mount a well-centered lens in a tube made concentric within the tolerances of modern machine shop work. This is quite logical, since a maladjustment of the amount which could occur here is quite insignificant in a terrestrial telescope, and especially insignificant in a low-power instrument.

In testing the concentricity of the various lenses in a telescope, a frequently useful method is to place a second eyepiece over the eyepiece of the instrument, and thus to examine the exit pupil of the instrument with the second eyepiece. Usually the various lenses and diaphragms throughout the system will be in sufficiently clear focus to judge their concentricity with considerable accuracy.

The test for lack of collimation is the quality of the image given by the instrument. This involves a test for definition and resolution. The best test object is a star, real or artificial. If the star is artificial, it should be made as small as possible, as this will increase the accuracy of the test. A very small pinhole may be made by laying a dozen thicknesses of tinfoil on a glass surface, and then puncturing the pile with a needle which has been carefully ground to a fine, circular point on a fine abrasive stone. The needle is thrust through a cork and then pressed down through the tinfoil. It will slip in the cork before sufficient pressure is applied to blunt the needle on the glass. The tinfoil is then separated, and the piece containing the smallest and roundest hole chosen, after an examination under a magnifier. This pinhole is then mounted in front of a bright light and set up at a suitable distance for testing. The distance should be as great as possible, in no case less than 50 times the focal length of the instrument objective, if the instrument is a telescope intended to be used on a distant object. The general rule is that the target or test object should be at the same order of distance as the object upon which the instrument is directed when in use.

The image formed of the star by the instrument in question is studied under high power for flare and color, then is examined *out-of-focus*. The out-of-focus image of a star in a properly collimated instrument should show as a circular disk. If the lenses are well corrected, a pattern of concentric colored rings will be visible both inside and outside of focus. If the image is elliptical, and does not change the position of its major axis when the eyepiece is moved inside and outside of the focal point, then a lens is twisted in the plane in which the elongation occurs. If the major axis shifts through 90° between the inside and outside positions, then astigmatism is present.

353. The Collimating Telescope

For the collimation of the optical axis of an instrument into a particular position with respect to some external part, as well as in setting the eyepiece position of an instrument, the *collimating telescope* plays an important role. The collimating telescope is a small telescope whose optical axis is carefully adjusted to coincide with the geometrical axis of its outer tube. It contains a straight cross-hair reticle and although its magnifying power is purely arbitrary, it is well that it should be fairly high, about 10X for most cases. Its purpose is to establish a definite direction of sight through the instrument (fig. 201).

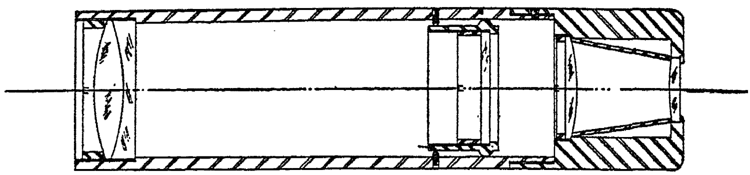


FIG. 201

The collimating telescope

354. Collimating to a Mechanical Axis

In some cases, it is desirable to collimate the optical axis of an instrument parallel to or at a definite angle with some external criterion, such as the direction of a magnetic needle, the zero index of a scale, or some mechanical axis or surface of the instrument. This is usually done with the aid of an artificial target and a collimating telescope. The necessary equipment is the collimating telescope, fixtures for holding it and the instrument to be tested in definite positions, and a suitable target; the target in some cases being merely a distant object.

The principle involved is to determine a line of sight with the collimating telescope and then determine whether, when

the instrument in question is placed in its proper position with respect to the mechanical axis of the collimating telescope, the line of sight is unchanged. Usually it is desirable to place the instrument with its eyepiece in front of the collimating telescope. Since the light emerging from the eyepiece of a telescopic instrument is in parallel bundles, the final image of the telescope may be considered to be a virtual image at infinity, and a collimating telescope adjusted for infinity will yield a clear image when it is placed behind the eyepiece of the instrument.

The actual mounting procedure will be different for each sort of instrument which may be tested, so that it is impossible to describe a definite procedure. However, an example will perhaps best illustrate the basic principles. Let us suppose that it is desired to collimate a gunsight with its locating surfaces, that is, to ascertain that the optical axis of the sight is parallel to the two locating surfaces on its base.

A surface plate is cross levelled with a sensitive level and the sight placed on it, upon its locating surfaces. A small V-block is found which will hold a collimating telescope at the same height as the telescope of the sight. A direct view through the collimating telescope will determine some point which is directly upon the horizontal line of its reticle, or, if no such point can be located, a target consisting of a short horizontal line may be set up at any convenient distance. The sight is then placed in front of the collimating telescope, resting on its locating surfaces, and another observation is made. If the test object is still on the horizontal line of the collimating telescope, the sight is properly collimated. If not, the optical axis of the sight is not parallel to its locating surfaces, and an adjustment is called for. It may also be necessary to adjust the reticle of the sight to coincide with the target line.

It is not really necessary for the surface plate to be leveled for this test, but it is good practice always to level a surface plate as a matter of course, for many adjustments and tests require that it is level. It is also easier to work upon a level

plate. It is not necessary that the collimating telescope in this test is at exactly the same height as the eyepiece of the instrument, only that there is some light entering the collimating telescope from the eyepiece of the instrument. Fig. 202 shows the setup for the test.

It should be noted that this will align the sight only in a vertical direction. No alignment in the horizontal direction was determined. This would usually be provided in the mounting of the sight to the gun, since there would be no locating surfaces on the side of the instrument.

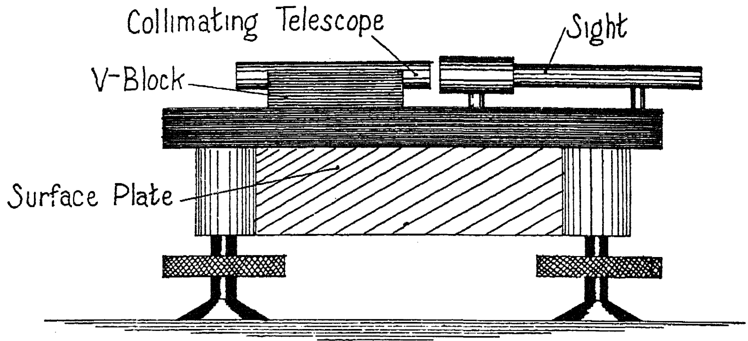


FIG. 202

Optical arrangement for collimating a gunsight

355. Adjustment of the Collimating Telescope

It is evident that the collimating telescope used in these tests must be very carefully made. Not only must its outer surface be concentric with its optical axis, but its reticle must be carefully centered. When rolled in a V-block the reticle must appear to rotate about its center, and the center must remain directly upon a given distant target point.

A simple method of achieving this is to mount the completed collimating telescope in a lathe, preferably in a chuck with individually adjustable jaws. If the lathe head-stock is hollow, and the eyepiece is mounted to the right. one may look through

the instrument at a target on a distant wall (the farther away the better). The telescope is then adjusted in the lathe until, when it is rotated, no movement of the target in the field of view is present. The reticle is then centered by means of its adjusting screws until its center coincides with the center of rotation. The outside of the collimating telescope is then turned down on the lathe, with every assurance that it will be concentric with the optical axis, since it is now the optical axis about which the telescope is being rotated. The method is the same as that used in edging optical elements. (329).

356. Collimators

The above procedure is adaptable to the case where only one or a few of a given type of instrument are to be collimated. In cases where a large number of a given instrument are to be collimated, as in an instrument manufacturing plant, it is helpful to have an artificial target in the form of a *collimator.* A collimator is the same as the collimator on a spectroscope (235), merely a well-corrected objective lens with a suitable reticle in its principal focal plane, illuminated from an outside source. This device has the effect of placing a well-defined target, the collimator reticle, at infinity. In this case, the collimating telescope will be permanently fixed with its optical axis parallel to that of the collimator, and a suitable fixture provided to hold the instrument to be tested in the proper position. Of course, the surface plate itself, and other mechanical apparatus incidental to the test, must be accurately machined, as the test can only be as accurate as the sum of the maladjustments of the fixtures used. In a permanent setup for the test described above, the surface plate would be replaced by a fixture to hold the test instrument in the proper position. This fixture would be aligned by the use of a gunsight known to be correctly adjusted. The collimator may be used merely as a substitute for a distant object, thus making possible the adjustment of instruments inside a closed building, by the

procedures illustrated in the example. A collimator is an almost essential tool for anyone adjusting optical instruments frequently.

COLLIMATION OF BINOCULAR INSTRUMENTS

357. Principles

The proper adjustment of binocular instruments requires that the optical axes of the two telescopes is parallel to one another in all positions of the interpupillary adjustment (except binocular microscopes with converging tubes). Since most of such instruments attain interpupillary adjustment by mounting both telescopes to a hinge, it follows that both optical axes must be parallel to the axis of this hinge, in order to maintain parallelism between themselves in all positions. It should be remembered that it is not sufficient to adjust the two telescopes for parallelism at *one* interpupillary setting.

358. Factory Methods

The collimation of binoculars in the manufacturing plant is invariably done with the aid of twin collimators permanently set parallel to one another. The lenses of the collimators must be sufficiently large to permit the binoculars to be rotated on the hinge through a complete movement, unless *three* collimators are provided. The collimating telescope may be single, and movable from one eyepiece to the other without changing its direction, or there may be a collimating telescope for each collimator, permanently adjusted parallel to it. There are many individual arrangements of binocular collimators, all corresponding to the basic principle that there must be *three* parallel lines of sight, one for one of the binocular telescopes and two for the other, corresponding to its two positions at the extremities of the interpupillary adjustment (fig. 203).

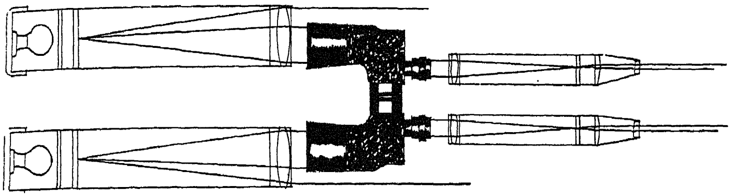


FIG. 203

Principle of the binocular collimator

359. Methods of Adjustment

Collimation adjustment in binoculars is achieved either by adjustment of the Porro prisms or by rotation of the objectives on eccentrics, or both. In the type provided with eccentrics, usually the objective cell is eccentrically bored, and mounted in an eccentric ring, which in turn fits into the adapter which is attached to the body. By means of these two eccentrics, the optical axis may be shifted anywhere inside a circle about 1° in diameter (fig. 204).

It frequently happens that this eccentric movement is not sufficient to collimate the instrument, due to maladjustment of the prisms, and in these cases, it will be necessary to adjust the prisms themselves. If no adjustment is provided, as is often the case, resort must be made to shimming individual prisms or the prism assembly as a whole. This is at best a makeshift method of adjustment, but sometimes necessary. It is better to do a little machining in the proper places if a machine shop is available. In a factory, replacing prisms with others slightly larger or smaller or with a different angular error is a common means of adjustment, but this may not be available to the individual worker.

The prism adjustment for collimation consists of tipping the prisms or moving them parallel to their hypotenuse faces. On no account should the prisms be rotated about an axis

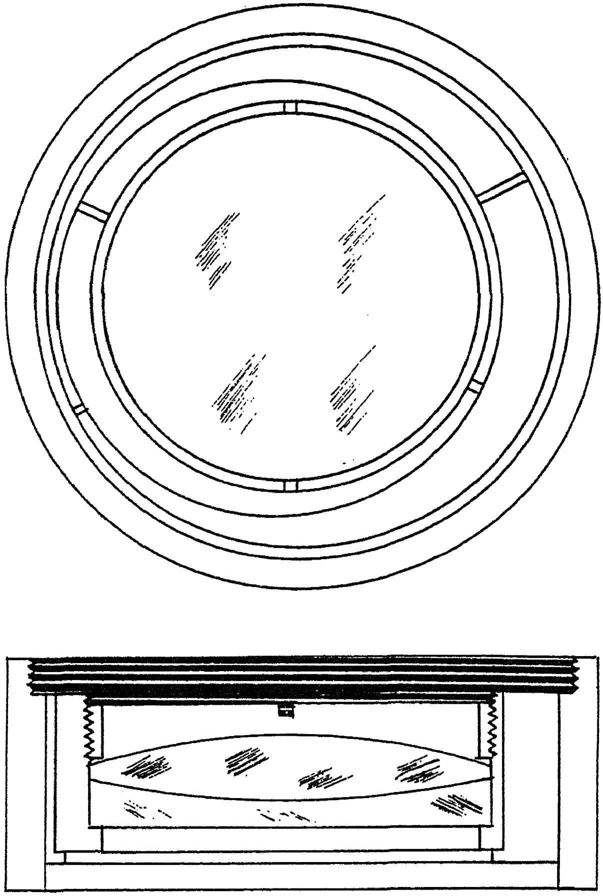


FIG. 204

Eccentric objective mountings (exaggerated)

perpendicular to the hypotenuse, as this will introduce tilt (216).

360. Practical Methods of Collimation

Binoculars may be collimated without recourse to the expensive equipment used by the manufacturer. All that is neces-

sary is a fixture to hold the binocular firmly, and another fixture, holding a collimating telescope, which is arranged to slide from side to side first behind one eyepiece of the binocular and then the other. If the instrument is properly collimated, the reticle of the collimating telescope will intersect at the same point in the field of view for both left and right telescopes.

A collimation of this sort merely assures that the optical axes of both telescopes will be parallel with one another, and does not assure that they are parallel with the axis of the hinge. To accomplish this, there must be two collimating telescopes, as shown in fig. 205.

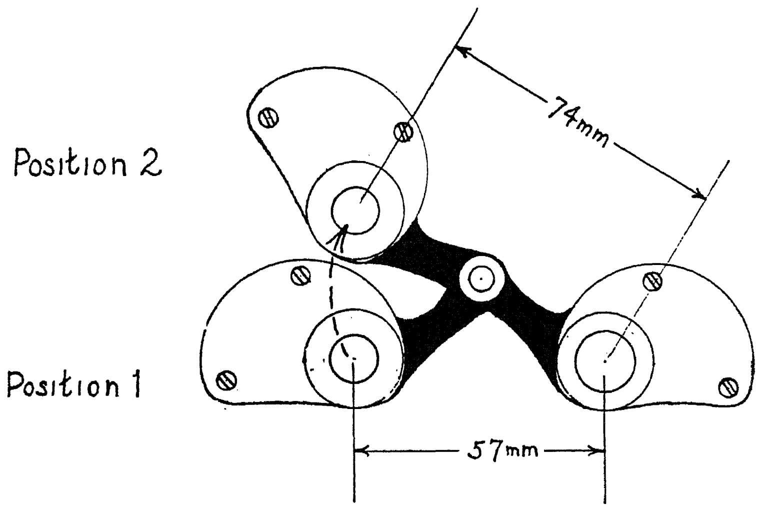


FIG. 205
Principle of binocular collimation

361. Tolerances

Tolerances, of course, vary with the individual creating them. It is generally accepted, however, that the optical axes of a binocular should be parallel within 3′ in a vertical direction, convergent at the eye end not over ½′ or divergent not over 3′ in a horizontal plane.

362. Inspection

Lack of collimation in a binocular results in the phenomenon of *double vision.* Since the eye will automatically compensate for a considerable amount of double vision, unless it is an extreme case, this will not be evident through ordinary use of the instrument except that the condition will cause severe eyestrain if the instrument is used continuously for any length of time. There are several methods for determining the presence of double vision.

If a bad case exists, it will be immediately evident through ordinary use of the instrument. An extremely sensitive method, but unfortunately not a very dependable one, is as follows: Place the eyes at their proper position behind the eyepieces of the instrument and look at a well-defined distant object, the instrument being placed upon some firm object, or in a fixture. Cover one objective for a few seconds and then uncover it suddenly. If double vision exists, there will be two distinct and separated images of the object seen, which will presently merge as the eyes adjust themselves. The theory of this method is that the eyes, when relaxed, have parallel optical axes. The fact that different individuals and even the same individual at different times show discordant results on this test is sufficient to show that this theory is not strictly true.

Another method is to place the binocular on a support and then examine the position of a given object in both fields of view. The difficulty with this test is that the only part of the field of view which can be precisely noted is the extreme edge, and the size of the field of view may be slightly different in the two telescopes, due to a possible slight variation in the size or position of the field stops. Furthermore, since the field stop diaphragm is usually attached to the eyepiece, it will move with it, and the size of the field of view (angular) will change with the position of the eyepiece as it is moved in and out for focusing.

The only really accurate method is through the use of the collimating telescope, clamped so that it can be moved first behind one eyepiece, then behind the other without shifting its direction. Then the object bisected by the reticle of the collimating telescope should be the same in both fields of view.

In the case of the binocular microscope the test object must be on the stage, and not at infinity. The same test can be made with the parallel tube type. With the converging tube type, cross hairs are placed in *each* eyepiece and a given object thus centered in both fields of view. If a circular target is used on the stage, this may be centered in both fields of view and collimation thus attained without the reticles. Since the binocular microscope has only one objective, adjustment for collimation must be made through the prisms.

363. Tilt or Lean

A maladjustment possible in most instruments containing prisms, or mirrors, and, therefore, prevalent in binoculars, is *tilt,* or *lean.* It is the condition where the image is not upright, but leans to one side or the other (see fig. 177). In any optical instrument, there are always an equal number of inversions in two perpendicular planes, and because of the equivalence of inversion and rotation (84) if these planes of inversion are not *exactly* perpendicular, rotation of the field of view or tilt will be introduced, equal to 2θ, where θ is the error in perpendicularity.

This condition can never occur in a lens, nor in a prism erecting system which is composed of a single element, such as a roof prism (unless there is an error in the prism itself, which cannot, of course, be adjusted for). The condition, therefore, is found in instruments containing mirrors or separated single-inverting prisms. In such instruments, adjusting methods are provided upon the mirrors and/or prisms to permit the removal of tilt. For this adjustment, the prisms must be

rotated about an axis lying in the plane of incidence. In the case of Porro prisms, the most prolific source of tilt, the adjustment calls for rotating the prisms as shown in fig. 132.

364. Inspecting for Tilt

A rapid inspection for tilt is to look through the instrument from the objective end, holding the instrument at some distance from the eye and observing a continuous line. The line may be seen through the instrument and also may be seen by the eye directly on either side of the instrument. If a maladjustment is present, the portion of the line seen through the instrument will be tilted with respect to the remainder. By looking through the objective end, the entrance pupil becomes the exit pupil, and being usually larger than the real exit pupil, provides a better view.

The above method is inadequate to detect a small amount of tilt (less than 1–2°) and since for optical measuring instruments the tolerance is usually 1–2′, these instruments must be checked for tilt with a collimating telescope. The collimating telescope is first adjusted upon a plumb line, so that its reticle is vertical. Then the instrument to be tested is placed in front of it and the plumb line observed again through both the instrument and the collimating telescope. If the plumb line does not still appear parallel with the vertical reticle line of the collimating telescope, tilt is present.

365. Definition and Resolution

It is difficult to set tolerances for definition and resolution for an instrument in general. The sharpness of the image to be expected depends upon the quality of the instrument, and in the absence of any standard for a given instrument, it is difficult to decide whether a certain degree of fuzziness is due to maladjustment or to poor design. In an instrument of good quality, the field of view should be sharp and distinct under any magnifying power recommended for the instrument. Tests should be made on the type of objects upon which it

is to be used. Even high-quality instruments intended to be used for terrestrial observation have rather large aberrational tolerances and might not show up at all well on a star-image test. The inspection of the instrument, when it has been known to be in perfect adjustment, will, of course, provide a standard.

For terrestrial instruments, the best sort of test object is a target with finely ruled parallel horizontal and vertical lines. If such a target is set up at a proper distance, the resolution may be checked, but it must first be known what degree of resolution may be reasonably expected of the instrument. It is extremely rare that an instrument is expected to reach its full theoretical resolving power (411). This target will also show any astigmatism or distortion which may be present.*

If it is impossible to bring the field of view into focus, then the objective or the erecting system is out of position with respect to its distance from the eyepiece. If astigmatism is present, some lens is probably twisted in its cell, or strained by being pressed in too tightly by its retaining ring. Distortion or curvature of the field are probably due to a lens having been reversed in its cell. Chromatic aberration may be due to improper spacing of eye and field lenses in the eyepiece. Spherical aberration (which shows up merely as poor definition), coma, etc., may be traceable to any of these causes.

The position of the eyepiece for best definition of a distant object for a normal eye should be near the center of its focusing movement. By the use of a collimating telescope, any abnormality of the observer's eye is compensated, since a clear image in the collimating telescope is possible only if light entering the objective is in parallel bundles.**

*If targets are set up at close range, parallax (367) may make testing difficult. If the eyepiece is fitted with a cap containing a very small central hole, it will be found helpful.

** This is not strictly true. The collimating telescope, in actuality, magnifies the error of the instrument under test by a factor which is, with close approximation, the square of the ratio of focal length between the objective of the collimating telescope and the eyepiece of the instrument under test.

It should be remembered in making such tests that an optical system is designed to operate at a definite range of object distances, and that aberrations, especially distortion, are likely to be present when the instrument is used on a target at a different distance. Targets or test objects should be reasonably far away, preferably at a great distance, when the range of operation of the instrument includes infinity.

At the end of this chapter there is appended a list of optical malfunctions and their most common causes. It should be noted that this is a list of malfunctions due to improper manufacture. If an instrument is being repaired, and has been known to have performed satisfactorily on previous occasions, it is obvious that whatever malfunctions may be detected, they cannot be due to causes such as are listed in this table, their causes, unless parts have been damaged, must be improper assembly by the repairman.

366. Focusing Movement, Diopter Scales

It was pointed out in (154) that many focusing eyepieces are provided with scales, known as diopter scales. The markings indicate the refracting power of the instrument in diopters (69) for that setting of the eyepiece. For example, at a setting of –2 dptr. the eyepiece is forming a virtual image at a distance of ½ meter in front of the secondary principal plane of the instrument. The purpose of these scales is to permit an observer to set off the proper correction for his eyes without the necessity of focusing the instrument upon an object. It is rarely, however, that they are made use of in this way, and furthermore, most manufacturers mark diopter scales in equal divisions, whereas the equation (15) is not linear.

The diopter scale should be set at zero with the eyepiece in the position where a sharp image of a distant object is seen through a collimating telescope, that is, at the point where the instrument is focused for infinity. For instruments other than telescopes, of course, the distant object does not

apply. In every case, however, the light coming out of the eyepiece should be in parallel bundles (i.e., virtual image at infinity) when the diopter scale is at zero.

367. Parallax

Parallax is defined as the condition which exists when the reticle is not coincident with the plane of the real image formed by the objective or the erecting system. Any separation of the image from the reticle causes the position of the reticle against the image to depend upon the position of the observer's eye within the exit pupil and, of course, makes measurement subject to error. The simplest and best way of inspecting for parallax is to look through the instrument at an object at the proper distance, and then shift the eye slightly from side to side or up and down, taking care, of course, not to bring the eye out of the exit pupil. If the two planes are not coincident, the reticle will appear to shift back and forth across the field of view, or vice versa.

If the reticle moves to the left when the eye moves to the right, then the reticle is nearer to the eye than the image, and if the reticle moves *with* the eye, it is farther away. The adjustment necessary is to change the distance between the objective (or erecting system) and the reticle, by moving either the objective (or erecting system) or the reticle in the proper direction.

This method of testing for parallax is useful in focusing a camera very accurately, as described in (175).

Another method of inspection is by using a collimating telescope, to determine whether both field of view and reticle are clearly defined at the same position of the eyepiece. If the eyepiece has a diopter scale, the amount and direction of movement of the eyepiece necessary to bring reticle and field of view successively into focus indicates the amount and direction of adjustment necessary.

Defects in Single Lenses

Effect	Probable Causes
Color fringes around objects and/or field of view	Poorly designed system, achromatic combination required
Vertical and horizontal line not in focus simultaneously	Astigmatism. May be caused by poorly designed system, cylindricity of lens, or by lens not mounted straight
Double images	Poorly annealed lens or a roof prism with improper roof angle
Blurred images of points	Spherical aberration or coma, due to bad design, poor manufacture. Shifting diaphragm may remedy
Images at center and edge of field are not in same plane	Curvature of field. Poor lens combination
Image shifted off center	Poorly centered lenses
Flare spot in field of view	Lenses not collimated, or distances incorrect

CHAPTER XXX

Mechanical Adjustment and Maintenance

368. Mechanical Construction of Optical Instruments

Practically all optical instruments can be disassembled without damage; they are assembled with screws, pins, etc., and not with rivets or press fittings. The reason is that it is impossible to make optical elements completely interchangeable and rather wide tolerances must be provided in the mechanical construction for the proper precise adjustment of the optical elements. Also provision must usually be made for fine adjustment of optical elements after assembly. Optical instruments are on the whole rather expensive, and repairs are usually more economical than replacement. Optical instruments are assembled almost exclusively by means of screw threads and taper pins. They are, therefore, easily disassembled without damage if a few ordinary precautions are observed.

369. Instrument Tools

For the proper repair of optical instruments, the following tools should be available:

Reamers	Steel rules
Punches	Thickness gages
Needle files	Thread gages
Taps and dies NF and metric	Depth gage
Drills	Vernier calipers
Micrometers, English and metric	Screw extractors
Jewelers' saws	Sharpening stones
Combination square	Calipers
	Socket wrenches
	Clamps and vises

- Hammers, hard and soft
- Drifts
- Screwdrivers
- Jewelers' screwdrivers
- V-blocks
- Adjustable wrenches
- Spanner wrenches
- Scrapers
- Tweezers
- Jewelers' Loupe (magnifier)
- Soldering iron
- Cape chisels
- Pliers
- Needlenose pliers
- Levels
- Hacksaws
- Center punch
- Pin vise
- Scribers
- Collimating telescope

and the following supplies:

- Modeling clay
- Alcohol
- Shellac
- Watch oil
- Sealing wax
- Brushes
- Sealing compound
- Gypsum
- Glycerine
- Grease
- Cleaning solvent
- Cloths or lens-drying tissue
- Indelible pencil
- Paint

In addition, a small lathe and drill press, with suitable accessories, will be found helpful. Not that all these tools will be required for a single job, but any one of them may be required, and should be available.

The necessity of using the proper tool for the job to be done cannot be too strongly emphasized. Every tool has a definite purpose and definite limits of capacity and should be used only for that purpose and within that capacity. Otherwise, irreparable damage may be done to the instrument.

370. Spanner Wrenches

A type of tool very frequently used in instrument work is the spanner wrench. Various parts, such as retaining rings and plugs, cells, and the like, which are annular in form and are to be screwed below the surface are handled by means of slots or holes in the rim. Slots require flat spanners, holes require pin-face spanners. There are no standard sizes for re-

taining rings and cells, therefore adjustable spanners must be used, unless the number of a particular instrument to be worked upon justifies the preparation of special tools (fig. 206). Even adjustable spanners are not standard tools, and

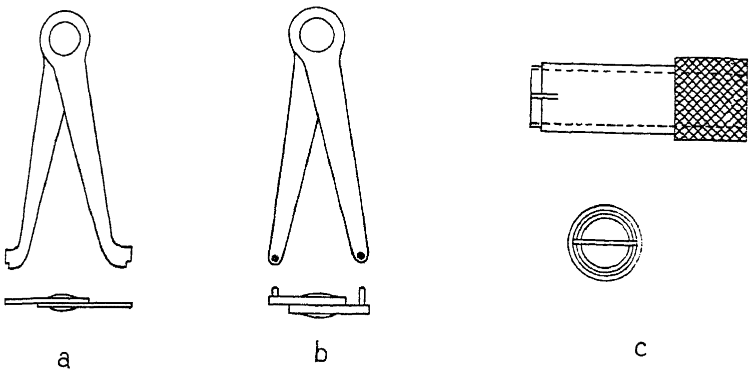


FIG. 206

Spanner wrenches

usually must be made to order. In the flat type, a shoulder should be provided to prevent the side of the spanner from scraping against the internal threads of the tube and damaging them.

371. The Use of Screwdrivers

It is assumed that the reader is familiar with the use of tools, but a few words with reference to the proper selection and use of that most frequently misused tool, the screwdriver, may not be amiss. The screwdriver is as much a precision tool as a twist drill, and as much care should be given to its selection. A screwdriver should be selected which has a blade a few thousandths of an inch narrower than the length of the screw slot, and which fits the slot snugly. The use of a screwdriver with too narrow or too thin a blade can only result in damaging the edges of the screw slot, and may cause the head to be

twisted off, making the removal of the screw a difficult task. It will be seen that the worker must provide himself with not a few, but a large number of screwdrivers of different sizes. Even so, there will be cases where none of his screwdrivers properly fit a given screw. In such cases, a few minutes spent grinding a screwdriver to the proper size and shape may save hours of work removing a broken screw.

The blade of a screwdriver should never be permitted to become bent or worn. The sides and edges of the blade should be straight and square. Screwdrivers require regrinding as frequently as cutting tools.

372. Removing Broken Set Screws

Every precaution should be observed to avoid breaking off the heads of set screws when attempting to remove them. The screwdriver should be of the proper size and should be held firmly in the slot and turned with a steady pressure. Nevertheless, in spite of precautions, set screws do become broken and must be removed by other means.

Screw extractors furnish the best method. Sometimes a screwdriver blade held in a small drill press will remove a screw (not broken) where hand pressure will fail. Drilling out the screw is a last resort. A drill somewhat smaller than the root diameter of the screw should be used, and the hole then retapped to its original size.

373. Worms and Worm Wheels

The worm and worm wheel mechanism is frequently found in optical instruments. The worm shaft usually contains a ball, which, engaging in a socket, permits the worm to be thrown out of mesh so that the wheel may be revolved freely when desired. A lever and cam is usually provided for this purpose. A spring and plunger holds the worm in mesh. Occasionally, the worm may be mounted on eccentric bushings to provide for disengagement and proper mesh (fig. 207).

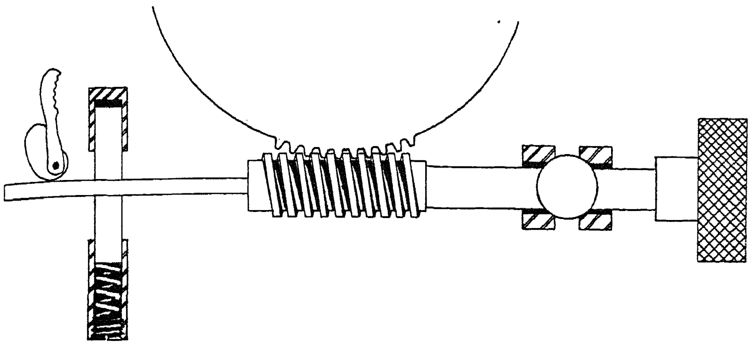


FIG. 207

Worm and worm wheel mechanism

One method of fine scale reading is obtained by mounting a divided circle (micrometer) on the worm (262). When this is done, the worm wheel must contain the same number of teeth as the divisions of the main scale mounted upon it or, occasionally, half this many teeth, when the scale is double.

374. Backlash

One of the most prevalent mechanical malfunctions of optical instruments is backlash in gear, worm, and screw mechanisms. Backlash is movement of a mechanism without corresponding movement of a coupled mechanism. When the threads of a worm, for instance, are loose in the teeth of the worm wheel, the worm must be turned a certain distance before the worm wheel begins to move. This is backlash, and if a micrometer scale is attached to the worm, incorrect readings will result. Even if there is no scale on the driving member, the driven member is not held firmly in position, and can move back and forth a slight amount, which may result in a shift of position between the time of taking an observation and reading the scale. Backlash, therefore, should never be allowed to exist in an optical instrument.

Since backlash is the result of improper fitting of gear teeth or screw threads, the necessary repair procedure is to fit these parts properly. In bad cases, replacement of one or both of the parts may be necessary. This is especially true of screws. Usually the female thread is in a portion of the instrument difficult or expensive to replace, in which case it may be rethreaded to a slightly larger diameter and a new male member provided to fit it. If the male member carries a micrometer scale, however, it must be remembered that the pitch of the thread has a definite relation to this scale and should not be changed. In the case of gears, replacement is usually necessary, since there is rarely any provision for bringing the hubs closer together.

In the case of worms and worm wheels, the most prevalent source of backlash, means are provided for adjustment to take up wear, as in the spring and plunger assembly and the eccentric shaft. This adjustment will, in general, be sufficient to take up any backlash which may be present. But the adjustment may be prevented from operating because the teeth of the worm and worm wheel do not fit each other properly. The most usual case is *bottoming*. Because of wear on the sides of the teeth, they have become narrower, and in order to maintain contact at both sides, they must be thrust farther into the matching teeth. But the end of the teeth may strike the bottoms of the grooves before the side contact is attained. This condition can be corrected by shaving off the crowns of the teeth of the bottoming member. It is more or less general practice to make worms of steel and worm wheels of brass or bronze, in which case the worm wheel will wear most rapidly, and the worm will bottom in the worm wheel. This requires that the worm be reduced slightly in outside diameter. It is put in a lathe and turned down with a cutting tool or abrasive paper or cloth.

When the matching teeth are fitted together, it should be possible to see light between the crown and groove of the teeth.

The sides of the teeth must also fit properly. In cases where a great deal of wear occurs on a small portion of the worm wheel, it may be necessary to scrape the teeth on either side of the worm region. Backlash is frequently removed by *lapping* (380).

375. Endplay

Endplay is the name given to endwise movement of a shaft. In general, it should not exist in the mechanical parts of optical instruments, although unless a thousandth of an inch or so is left between shoulders and bearings, the mechanism may be to stiff to operate. Shafts are held in position endwise by shoulders, collars, or thrust bearings, or a combination of these. Tightening of collars and bearings, or replacement of parts, is necessary to remove endplay. Endplay sometimes occurs in worm and worm wheel mechanisms due to looseness of the ball in its socket. Tightening of the cap (see fig. 207) is sufficient to remove play here.

376. Bearings

Bearings in optical instruments are nearly always smooth surfaces. Ball and roller bearings are infrequently found. It is evident that bearing surfaces should not contain high spots, burrs, or scratches. Scraping and lapping are the methods of correction of such defects.

377. Cleaning of Mechanical Parts

Whenever an optical instrument is disassembled, its mechanical parts should be thoroughly cleaned of all dirt, dust, moisture, grease, oil, sealing compounds, etc., and relubricated and resealed when reassembled. Gasoline and kerosene are common and inexpensive solvents for most foreign matter. The removal of shellac, wax, and other sealing compounds may require the use of other solvents, such as those mentioned for the cleaning of optical elements (343). Parts should be

soaked in solvent for several hours, removed, washed with fresh solvent, and dried. If parts are not delicate, a good brushing in solvent with a stiff brush (not wire) before the soaking is recommended. Parts may be dried with clean *lint-free* rags, or with an air stream if this is available. All traces of solvent must be removed before reassembly.

378. Threaded Members

All burrs and scratches on threaded members should be removed with taps and dies of the proper size. Set screw holes are especially subject to damage during the removal of the screws, and should always be run through with a tap before reassembly. All damaged screws should be replaced. Set screws are easy to make out of wire with a threading die and a jeweler's saw, and there is no excuse for placing a damaged screw in an instrument where it may give trouble at the next disassembly.

379. Filing and Scraping

Filing and scraping, when necessary, must be performed with care and skill, or the result will be worse than before repair was attempted. Numerous texts on shop practice will give proper techniques of filing and scraping, which the reader should consult unless he is already a competent workman.

380. Lapping

Lapping is the process of grinding two parts together with an abrasive until they fit smoothly. There are many types of lapping compounds available, including carborundum, emery, pumice, etc. Any lapping compound used on parts of optical instruments should be of very fine grade, and used without violence.

All lapping compound must be removed after use by gasoline or other solvent and vigorous brushing. Lapping is not recommended upon soft metals such as brass or aluminum because

the abrasive embeds itself in the metal and is not removed by cleaning, causing subsequent abrasive action during operation of the parts. Brass and aluminum parts should be fitted by scraping (379).

381. Lubrication

Upon reassembly of an instrument, all working parts should, of course, be properly lubricated. Watch oil is usual for shafts, plate bearings and gears. When the parts where lubricant is to be used have direct access to any opening in which optical elements are present, however, grease instead of oil should be used, to lessen the possibility of the lubricant finding its way onto the surface of a lens or prism.

No one grease can be recommended for all cases. The principal facts to be borne in mind are that the grease should be adapted to withstand whatever temperature extremes the instrument may be called upon to undergo, that it is not to be used for lubrication of fast-moving parts and must, therefore, retain its viscosity under slow movement and considerable pressure, and it must contain no volatile components which may condense upon lenses and prisms.

It is very important not to overlubricate. Only a thin film of lubricant should be provided, and all oil or grease should be removed from exposed parts, to avoid undue collection of dust. In addition to working parts, all screw threads, including set screws, should be lubricated with grease before assembly. The grease not only lubricates but acts as a seal against the entrance of shellac or other sealing material onto the threads, preventing future disassembly.

382. Sealing and Plugging

All screw holes, joints, and external lenses should be sealed against the entrance of dust and moisture. A drop of shellac under or upon the heads of screws seals them in place against

loosening from vibration or temperature. Under no circumstances should shellac be placed upon threads.

A small amount of ground rubber added to a mixture of pitch and beeswax makes an effective sealing compound for lenses. Only external lenses, such as objective and eye lens of a telescope, need be sealed. A small amount of sealing compound is placed around the edge of the lens before it is placed in its cell. External joints may also be sealed with this compound.

Beeswax, sealing wax, modeling clay, etc., should be used to fill all screw holes after assembly. It is common practice to color this plugging compound to match the color of the paint of the instrument to make disassembly by unqualified persons more difficult and less likely.

383. Care of Magnetic Needles

Magnetic needles are occasionally found on optical instruments, and may require attention. Good needles contain a jeweled bearing in the center which fits upon a hardened steel pivot. Broken jewels and worn pivots should be inspected. A broken jewel must be replaced; pivots may be sharpened with a needle file. The needle itself should never be filed. Frequently needles are balanced by a drop of shellac applied to the underside. This should not be disturbed. A needle may require remagnetization.

A test for the proper operation of a magnetic needle is to release the clamp and watch the action of the needle. There should be a distinct *shimmy* and the needle should swing freely on the pivot with a period of not more than 3–5 seconds.

384. Level Vials

Level vials are frequently found on optical instruments. The vials are usually mounted in their frames, in gypsum, or plaster of Paris, and then a wooden or metal plug is inserted. Ad-

justing screws are provided either inside the frame or in the form of jack screws on the frame mounting.

If the level vial is removed from the frame or the frame from the instrument, readjustment will be necessary. A level line of sight must be provided by sighting at a sea horizon or an object of known height, and elevation scales set accordingly at zero. The level vial is then adjusted. If the instrument has horizontal movement, the vial must be adjusted to remain level throughout the complete traverse. Vertical travel of the instrument against a long plumb line is also useful in checking cross-leveling.

In the case of cross-leveling vials, the best method of adjustment is as follows: Working on one vial at a time, center the bubble with the leveling screws on the instrument, keeping the adjustment as closely as possible in the plane of the vial. Rotate the instrument through 180°. Remove half the error in the vial by means of the adjusting screws and the other half with the leveling screws of the instrument. Repeat until correct.

It is better to leave level vials untouched if possible, provided they are in proper adjustment. But the checks for horizontal and vertical travel (385) should be made in any case.

385. Horizontal Travel

When instruments provide movement horizontally and vertically with scale readings, checks for correct horizontal and vertical travel should be made. In checking for horizontal travel, a distant level line of considerable length, say, a sea horizon, is necessary. The instrument is moved on its horizontal motion and observation made to see if the horizontal reticle line remains level throughout the movement and remains on the target line. Occasionally it is possible to operate the horizontal motion without changing the direction of sight of the instrument, as in a theodolite, where the clamp may be released and the horizontal table rotated while the instrument

is held stationary. The horizontal reticle line should remain fixed upon a distant object during such movement.

386. Vertical Travel

Vertical travel is checked against a long plumb line by the vertical reticle line. Any variation in either horizontal or vertical travel calls for examination and treatment of bearing surfaces, adjustment of level vials or, in instruments where optical parts rotate with respect to one another through horizontal or vertical travel, adjustment of prisms may be necessary.

387. Adjustment of the Line of Sight

It is occasionally necessary to adjust the line of sight of an instrument with respect to its mechanical parts: For instance, the line of sight of a theodolite should coincide exactly with the direction of the magnetic needle when the latter is at the north index of its scale. Adjustment for this is usually made by moving the scale itself, but sometimes the adjustment consists of shifting the optical system or members of it.

Also, the line of sight of a theodolite should be level when the level vial on the telescope is level and the vertical circle is at zero. In a theodolite, one can adjust the level vial, although in some instruments, the adjustment might be made with an eccentric objective. The test is the examination of a distant target whose height is the same as the telescope of the test instrument. Such a target can be set with a master instrument, or with the instrument under test if two targets are set up and observations made alternately from one and then the other. A collimating telescope upon a level surface plate at a measured distance above or below the objective of the test instrument may be used to mark a target for this test.

388. Scales

It is frequently necessary to fill scales which have become dirty or worn. If need be, the markings may be repaired with an engraving tool. They are then filled by wiping a suitable scale filler across the scale, filling up the markings, and then removing the excess from the unmarked part of the scale with a clean rag.

White lead, with proper color pigments added, is a satisfactory scale filler. There are also products sold for this specific purpose. Remarking a scale should not be attempted if the former marks are invisible, except with a dividing head on a milling machine or lathe, or other suitable precision method, and even when the markings are visible, great care must be taken not to alter their position. Visible marks may be deepened with an engraving tool.

Occasionally, it is necessary to adjust verniers or micrometers to proper coincidence with the main scale at the zero position. Verniers are usually attached with screws passing through slots in the scale to permit such adjustment; micrometers are usually held by a clamping collar, which may be easily loosened and the micrometer scale rotated into the proper coincidence.

389. Finishes

Finishes applied to instruments vary greatly. Most frequently, major parts are finished in bright metal, the polish being retained with a coating of lacquer, usually baked. Lacquer preparations are available which are simple to apply and may be baked in improvised ovens. *Crackle* paint is very popular, and this is sprayed on and baked. A few inferior paints of the same variety are available which can be applied with a brush and dried in air. *Bluing* of brass parts is quite popular, and may be done by heating the parts in a solution of copper sulfate or copper carbonate. Baked enamel finishes are also frequently found.

PART IV

SUPPLEMENTARY TOPICS

CHAPTER XXXI

Notes on the Design of Optical Systems

390. Constants and Specifications

The general problem facing the optical designer is to plan an instrument to meet certain required specifications which can be constructed at reasonable cost out of available materials. The specifications will include magnifying power, resolving power, field of view, efficiency of illumination, and very probably there will be definite limitations as to overall size. Certain mechanical movements may have to be provided for, with appropriate scales, and a certain degree of accuracy will be required.

The first problem is to design the instrument tentatively in a mechanical way. This is not essentially an optical problem, and since it will vary widely in individual cases, no general rules can be laid down. The mechanical arrangement will probably lead to specifications concerning the optical system, and these having been determined, the design of the optical system itself can proceed.

391. Rough Design

The type of instrument contemplated will, in most cases, dictate the number and nature of the optical elements required. There are very few really new optical systems, and the experienced designer will in all probability make changes in the optical dimensions of an existing system. It is almost axiomatic that the finished system should be as simple an arrangement as will perform the required task.

392. Secondary Design

The next problem is to choose the dimensions of the various elements. The specifications as to magnification and field of view will decide the focal lengths of the lenses involved, the deviations to be produced will determine the prisms necessary, and the requirement as to field of view, resolving power, eye relief, etc., will determine the diameter of the components and the position and diameter of the necessary diaphragms. The entire system will then be worked out by thin-lens equations (see chapter VIII).

393. Finished Design

The designer is now ready for the major part of his task, that of designing the individual components of the system. The purpose for which the instrument is to be used will enable him to place specifications upon the degree of freedom from various aberrations which must be attained. The designer must choose the various glasses to be employed, and he will do this from standard lists wherever possible.

The procedure in designing an achromatic lens is as follows: the glasses having been chosen, the relative total curvatures of each component are determined by the achromatic condition. By plotting a graph of spherical aberration against curvature of a selected surface for each separate component, a two-line graph is formed, of which both lines will be nearly parabolic in form. If one component is plotted with the aberration reversed in sign, then the intersection of a horizontal line with the two curves indicates a lens combination which will be free of spherical and chromatic aberration. If the two curves cross at any points (and they usually cross at two points) this represents a *cementable* combination. It is thus seen that, in general, any two glasses will give *two* possible cementable combinations and an infinite number of *broken contact* solutions (111).

Since all the dimensions may be made relative to an arbitrary

standard, a single curve will suffice to give the complete data for a given kind of glass, and any established optical designer will have prepared curves for different glasses, so that it is a relatively simple matter for him to select an appropriate combination for a specific purpose. Experience will guide him as to the regions of the curve from which he must choose his combinations in order to achieve relative freedom from the oblique aberrations.

His next task is to check for the important oblique aberrations, which is not so simple a task, since the constants of the proposed optical system will be the deciding factors here. Choosing the position and dimensions of the diaphragms of an optical system are the most efficacious means of reducing the oblique aberrations. At this stage the designer must consider the system as a whole, and he may find it necessary to introduce chromatic and spherical errors in some of the elements to be compensated elsewhere in the system in order to achieve freedom from astigmatism, coma, etc. He may even at this stage find it necessary to add one or two additional elements to the system, or even to make a change in the glass specifications.

It is at this stage of the designer's work that his experience becomes an increasingly important factor, since it is often his only guide to a solution of his problem. Optical designing is often a problem of *cut and try* methods, since any attempt to set up a general mathematical formula for a complete optical system leads to hopeless complexities.

394. Adjustments

Every time a new batch of glass arrives at the optical shop, the designer must make small changes in the design of all instruments in which this particular glass is used, if the instruments are highly corrected. This is necessary because the constants of one pot of optical glass are never quite the same as those of another pot of the same kind. These variations

are in the fourth or fifth decimal place, but are still sufficient to cause a sensible difference in the performance of highly corrected optical systems such as apochromatic microscope and camera objectives. The necessary corrections consist of small adjustments of the radii of the various surfaces in the system. In the case of simpler instruments, such as terrestrial telescopes, the cheaper binoculars, etc., these small variations need not be taken into account, as the performance specifications are not very rigid.

395. Cost Factors

The actual grinding and polishing of a lens is not a very expensive proposition, as is evidenced by the low cost of the simpler optical instruments, terrestrial telescopes, low-priced cameras, etc., which are made in large quantities. The principal cost factor is the preparation of test plates and grinding and polishing tools, the cost of which may run well into four figures for a single small surface. When this cost must be spread over a relatively small quantity to be produced, and when the additional costs are considered which are involved in a change in several surfaces every time a new lot of glass is received, it is small wonder that really good instruments are expensive.

The competent and experienced optical designer can do much to reduce costs in the plant. Every established shop has a large supply of test plates and tools for surfaces produced in the past, and if the designer is worth his high salary, he will specify radii for which new tools and test plates must be made only in cases of dire necessity. For the most part, he will be able to specify radii for which tools and test plates are already in existence, and thus save the huge expense of preparation. It takes time to make these preparations, and time may be an important consideration. This is, more than anything else, the factor which keeps the old, established plants the almost exclusive representatives of the industry, except in war times,

when the huge quantity production then necessary makes the preparation costs economically worth while.

Again, the designer can save much time and trouble in the plant if he confines his specifications to surfaces easy to make. Steep curves are expensive and difficult to produce, and many times it is cheaper to make relatively slender lenses, and use two or more instead of a single fat lens. The competent designer will also avoid lenses whose surfaces are *nearly* but not quite alike; it is almost impossible in the plant to identify the proper surface without careful and time-consuming measurement. On the other hand, lenses with equal curvatures on the two surfaces are easy to produce; they require only one test plate and set of tools for both surfaces.

Designers have occasionally selected lens combinations where one component is of smaller diameter than the other, although they are cemented; the component which is smaller being inserted into the other. These are very difficult and expensive to produce, since they require special treatment in the plant. Triply cemented combinations should be avoided whenever possible, and it is almost always possible.

An image plane should never be located upon, or close to, an optical surface (except a reticle). If it is, every tiny and otherwise insignificant blemish in the surface becomes prominently visible, the perfection of the surface must be so great as to make it economically impracticable to produce it. Flat surfaces can be made perfect much more easily than curved surfaces. In one case in the author's experience, a double convex crown lens was to be inscribed with a reticle on one of the surfaces. This surface had to be polished to such a high degree of perfection that rejections in the plant ran as high as 80%. Production of a highly critical military instrument was all but brought to a standstill, not to mention the monetary losses concerned.

CHAPTER XXXII

The Manufacture of Optical Glass

396. Properties of Optical Glass

Optical glass is no different in general nature than glass used for a variety of other purposes, it is merely glass which has been very carefully produced with the intention that it should possess very specific physical properties. It must be homogeneous, chemically and physically stable, transparent, and its refractive index and dispersion must conform to definite specifications within a very small margin of error.

397. Imperfections

The imperfections in optical glass have definite names and properties. *Striae* are streaks of different composition than the remainder of the mass. They are usually of lower refractive index than the remainder, which is what makes them visible, and there may be a gradual change of index in their vicinity. Striae cannot be tolerated in roof prisms or highly corrected objectives although a few small ones may be tolerated in other elements. *Bubbles* are entrapped gases; if small, and not too numerous, they are not objectionable except if they occur near an image plane. *Stones* (inclusions) are particles of undissolved material. Their presence is very undesirable because of strains and pressures which they set up in their vicinity. *Strains* are set up by unequal cooling and are very objectionable because they may cause warping of a finished surface. *Color* indicates low transparency.

Because it is necessary to maintain a high degree of per-

fection in optical glass, it can be produced only in small quantities, made even smaller by rejection of from 25%–75% of each melt because of striae, stones, strains, and bubbles.

398. The Melt

Optical glass is made in batches of about 1000 to 1500 pounds. The raw materials: sand, potassium, sodium, calcium, and barium carbonate, boric acid, lead oxide and possible other ingredients are thoroughly mixed, and then added in small quantities to a clay pot for melting. The clay pots must be carefully made and selected, since a certain amount of dissolving of the pot material into the melt is unavoidable. Iron is the particular bane of the glassmaker, because it is present in small quantities in almost every clay, and its presence in optical glass causes undesirable coloring effects, giving to glass the green tinge which is indicative of inferior quality.

The pot is preheated in a furnace for 3–5 days at a temperature of 800–1000°C. It is then baked at 1400–1500°C for several hours, when *cullet,* rejected glass from a previous melt, is used to coat (glaze) the interior. The *filling-in* process with the raw materials takes place at about 1400°C. The material is added slowly as it melts.

The melting process then proceeds for about 24 hours, the mixture being stirred from time to time to remove bubbles and mix the ingredients thoroughly. During this melting and *fining* (removing bubbles) period, temperature control is the most important factor. When the melt has been thoroughly melted, mixed and fined, it is cooled to about 1000°C and then the pot is removed from the melting furnace and allowed to cool slowly over a period of about eight or nine days. It is then broken up, the pot being broken away from the glass, and it is found to be in chunks of varying size. It does not cool in a solid, clear mass, but is filled with cracks. Large, clear pieces are not common.

The pieces are trimmed with hammers and inspected for

striae, strains, stones, etc., the rejected and broken pieces being put back into the next melt as cullet.

There are two methods of preparing this glass: pressing and molding. In the case of pressing, it is heated to about 500–800°C, when it becomes soft and pliable. It is then patted into the proper shape and pressed into preheated molds. In molding, the blocks of glass are put into molds and then heated to about 1100°C for two to three hours. In both cases, the blanks must be *annealed,* cooled very slowly for several days to permit all internal strains to adjust themselves.

The glass blanks must be inspected carefully before shipment. For this process, one or more sides of the blanks are ground and polished, and then the blanks are examined under indirect or polarized light for imperfections. They may also be immersed in a liquid whose index of refraction is equal to that of the glass, and this process will eliminate the necessity of grinding and polishing.

399. Rolled Glass

An alternative method of producing optical glass is to pour it out of the pot when it comes from the furnace onto a large metal table and roll it with heavy metal rollers. This glass, too, must be carefully annealed. The rolling process is more economical but does not produce quite as high quality a glass as the other methods.

400. Properties and Formulae

The making of optical glass has progressed to such a high degree of perfection that almost any desired properties (within certain ranges) may be produced by a correct analysis of formula. It is often the case that an optical designer will specify glass of certain constants, not available on standard lists, and the glass maker will produce it without difficulty, if the desired properties are not extreme. There are certain general classes of optical glass subordinate to the main groups

of crown and flint, representative types of which are shown in the table accompanying (107). The borosilicate crowns, barium crowns and flints are the most important.

The characteristic ingredient of flint glass is lead oxide, the proportion of which may run as high as 80% in an extra dense flint glass. Borosilicates contain boron oxide, barium glasses, barium oxide. Silicon dioxide is the characteristic ingredient of all glasses, although recently Morey has developed new glasses with special properties which contain no silica whatever, but whose principal ingredients are the oxides of the rare earth metals, strontium, lanthanum, ytterbium, thallium, etc.

401. History

Originally, there were only two kinds of optical glass, crown and flint. Crown glass had a low index of refraction and a low dispersion, flint glass, high index and high dispersion. Physical density was such a good criterion of index of refraction that glass was customarily ordered and catalogued by density. Dispersion was taken as it came.

Abbé, who was one of the principal founders of modern methods in optical design, pointed out the desirability of procuring optical glass in which the dispersion was not so strictly proportional to the index of refraction, and O. Schott, of Jena, set out to produce it. It was here that the borosilicates and barium glasses originated, the original Jena glass, which for many years was an exclusively German product, and which made possible most modern optical instruments. Today the optical glass produced in this country is as good as any from Europe, a result of the research and development carried on during the first world war.

CHAPTER XXXIII

NOTES ON PHYSICAL OPTICS

402. The Wave Character of Light

It was stated in (5) that light is a wave motion, and, although this conception does not explain certain phenomena, it is sufficient to explain certain others, most significantly those involved in the operation of the optical instruments we have been discussing, and it is necessary to explain the phenomena of interference and diffraction. We have, therefore, for the purposes of this volume, accepted the wave theory of light, and made no reference to the phenomena which the wave theory cannot explain, except for a few remarks at the end of this chapter.

The waves of light may be likened to water waves, they are three- rather than two-dimensional. Such waves are known as *transverse* waves, because the direction of motion of the particles of the transmitting medium is at right angles to the direction of propagation of the waves. Of course, light is transmitted in the ether, which does not possess particles in the ordinary sense, so that the description is purely symbolical. The displacement of particles, in the case of light, is replaced by variation in the value of electric and magnetic vectors.

403. Definition of Terms

Transverse waves are characterized by *velocity, wave-length, frequency, amplitude, wave number,* and *phase.* The velocity of light is 186,283 miles per second, approximately, in free space. In other media, the velocity is less, is different for different wave-lengths, and is measured by the index of re-

fraction of the medium in question. The wave-length is the distance between a point on one wave and the corresponding point on the next. It is usually measured in *angstroms* (1 angstrom = 10^{-8}cm.). The frequency is the number of waves passing a given point in a unit of time, usually a second. It is, evidently, the velocity divided by the wave-length. When the velocity is reduced by passage through a material medium, the frequency remains constant and the wave-length changes. Either wave-length or frequency may be used as a measure in amplitude. When two wave trains of the same wave-length and low frequency being red and low in energy; that of short wave-length and high frequency being violet and of high energy. Frequency is the real physical property, wave-length is a spatial dimension which is more or less artificial. The amplitude is the maximum displacement of the medium, the height of the crest or the depth of the trough of the wave, and determines the intensity of the light. Wave number is the number of waves per centimeter, that is, the reciprocal of the wave-length. Phase is the particular point of the wave being considered. It is usually defined in circular measure, referring to the abscissa of the sine curve representing the motion of a particle of the medium.

404. Superposition

When a particle of the transmitting medium is acted upon simultaneously by two or more wave trains, its resultant motion is represented by the algebraic sum of the motions imparted to it by the separate wave trains. If two separate wave trains of the same wave-length are *in phase*, if crest coincides with crest and trough with trough, the result is merely an increase in amplitude. When two wave trains of the same wave-length are one-half a wave-length (180°) *out of phase*, the resultant motion of the particle is zero, and there is complete cancellation. In the case of wave trains of different wave-length traveling together, as in ordinary white light, the resultant motion of

the particles is represented by a complicated curve that has no similarity to the monochromatic (single wave-length) sine curve.

405. Interference

The superposition at a given point of wave trains from separate sources is known as interference. The term is not restricted to the case of cancellation but to all conditions of superposition of which the extremes are constructive and destructive interference.

Consider two separate light sources, s_1 and s_2, each emitting light of a specific wave-length and in phase with one another (fig. 208). The concentric circles represent the position of the crests of the two separate wave trains. From each of the sources, the space to the right is filled with light vibrations. At any given point in this region, the waves from the two sources are in a definite phase relation, which varies from point to point. It will be seen that the points (c) where the crests are coincident and the points (d) where crest meets trough, lie along straight lines directed outward from a point equidistant from the two sources. If a screen, MM′, is placed parallel to the line joining the two sources, and at any distance from them, it is clear that the screen will be illuminated by a pattern of light and dark areas, which will occur in concentric circles. The points (c) are the *maxima*, or bright areas, the points (d) the *minima*, or dark areas.

It is evident that C represents a point where the light from the two sources is in phase, that is, the distance $s_1C - s_2C$ is a whole number of wave-lengths, or, what is the same thing, an even number of half wave-lengths. Also, D represents a point where the distance $s_1D - s_2D$ is an odd number of half wave-lengths.

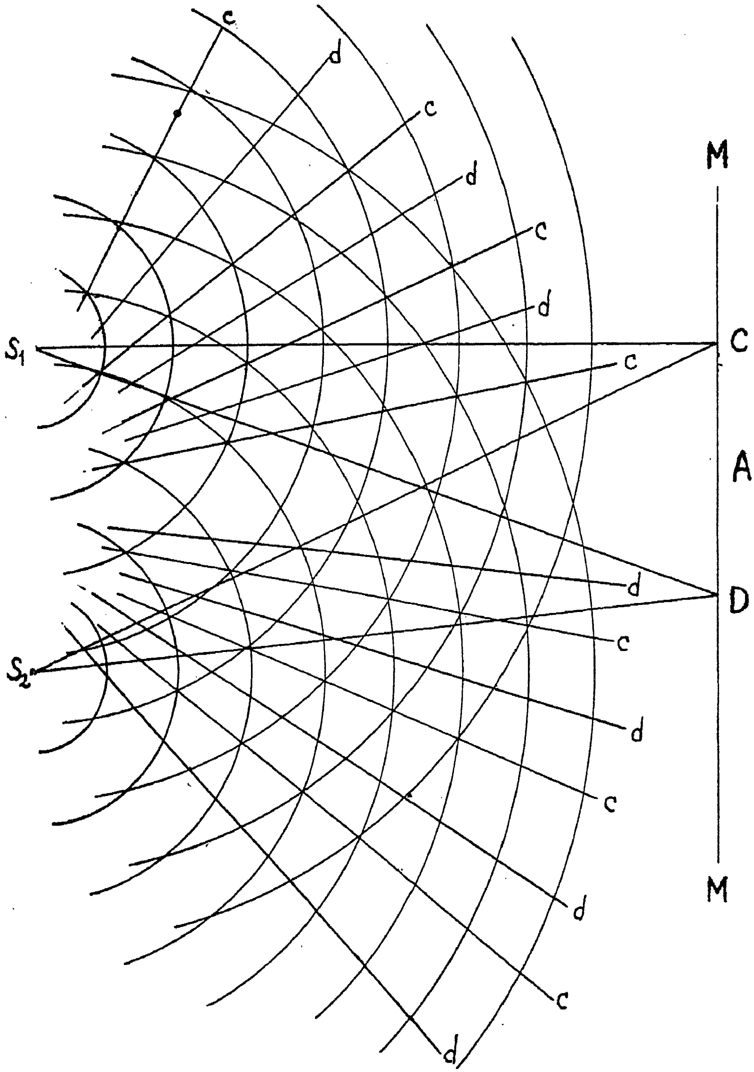


FIG. 208

Interference of light from two sources

406. Measurement of Wave Length

Since we may place the screen MM′ at any convenient distance from the two sources, we can always put it far enough away so that the distance AC from the perpendicular to the first maximum, C, is a measurable quantity. We can then apply the relation:

$$AC = \frac{\lambda}{2d}$$

where λ is the wave-length of the light.

It will be noted that the same result was obtained in (244) by a somewhat different process. The same phenomena explained in (244) can be deduced from the above: that the position of a maximum depends upon the wave-length of the light according to the equation:

$$\sin A = \overset{m\lambda}{\cdot} \qquad (40)$$

and that thus a *spectrum* is produced. Spectra are produced by *interference,* the method of approach used in (244) being introduced to avoid discussion of interference and diffraction at that stage. However the method of approach used there is perfectly valid.

407. Producing Interference

Interference patterns by two such sources as described above are produced in several different ways. The important fact is that the two sources must obtain light from an original single source, since no two independent sources will maintain the necessary synchronism of phase for more than a small fraction of a second.

The procedure, then, consists of splitting the light from a single source. The simplest method is merely to have two

pinholes or slits illuminated by light from a single pinhole or slit. A double prism or double mirror will form two virtual images of a single source which will be equivalent to two sources, or a single mirror will produce a virtual image which may be paired with the single source itself. For the satisfactory performance of these double slits, it is not necessary that the light leaving the two sources should be exactly in phase, only that there be a constant *phase difference.* The light, however, *must be monochromatic.*

408. Newton's Rings

Interference offers the explanation of the *fringes* that are used to test the perfection of optical surfaces (333). There exists a wedge of air between the surface to be tested and the test plate. Light reflected from the surface to be tested is superimposed upon light reflected from the test plate. The locus of all points for which the optical difference of these two paths is a multiple of λ will give rise to constructive interference, and therefore, a bright ring. When the light used is not monochromatic, the bright rings in different wave-lengths are of different diameter, hence the familiar colored fringes.

409. Rectilinear Propagation

The one difficulty which the wave theory of light encountered at the time of its propounding was an apparent inability to explain the observed fact of the rectilinear propagation of light. A wave motion does not travel in the form of a beam, it spreads out in all directions. But the facts of interference pointed definitely to a wave motion. As a matter of fact, light does not travel in a straight line, beam, but only appears to do so in the mass.

If we take a rectangular opening, a wide slit, and pass a beam of light through it onto a screen, we will see a sharp rectangle of light, a phenomenon which would lead us to conclude that

light continued in a beam in straight lines through the opening. But if we now reduce the width of the slit, until its width is not immeasurably large with respect to a light wave, we may be surprised to observe that the "image" on the screen becomes *wider* as the slit becomes *narrower*. Here our conception of rectilinear propagation fades away. A close examination of the edge of the image of the wide slit would have shown that it was bordered by colored bands similar to interference bands.

410. Diffraction. Definition

Phenomena of this sort, which indicate that light does not travel in a straight line, are known as *diffraction* phenomena. They are a direct result of the conception of secondary wavelets from each wave front (4). We already laid the foundation in our mathematical analysis in appendix I for the determination of the intensity at a given point P of the resultant of all the secondary sources along the wave front WW. Without going into mathematical detail, it may be seen that if the wave front were restricted in length, we should not be able to take our integration between $\pm 90°$, and in this case it might be expected that the intensity at a point P would depend upon the location of P.

The actual effect is a bright image at the center, flanked by bright fringes, which become less numerous and fade off in intensity more rapidly as the slit is made wider. The same effect takes place in the formation of images by ordinary optical elements, and explains why the resolving power of a telescope depends upon aperture. As we have seen, as the aperture of the experimental slit becomes greater and greater, the phenomenon of light transmission more nearly approaches the limiting case of true rectilinear propagation.

When we deal with numerous narrow openings, alternating with opaque areas, as in the diffraction grating, theoretical and experimental investigations show that the effect is to increase the distance between the bright fringes and to make

each fringe narrower and more sharply defined. These fringes then become the various spectral orders.

411. Resolving Power of a Telescope

Because of the effects of diffraction from a circular aperture, the image formed by a telescope objective of a point source of light is not truly a point, but a diffraction pattern of bright and dark fringes. The central maximum is by far the brightest, and the maxima fade off very rapidly, there never being more than two or three with any significant illumination. The image of a point, then, is larger than the source, and although theoretically two distinct points are always separated, this will not be true of the images of these points, these overlapping when they occur close together.

When the two images overlap, there is, in effect, only a single image formed of the two points. The limiting angular separation of two object-points which can be rendered as separate images by a given objective is known as the *resolving power* of that objective. By convention (although different observers will show slight disagreement) this limiting state is considered to have been reached when the central maximum of one image falls upon the first minimum of the second. By extended mathematical theory this can be shown to be given by:

$$\sin \theta = \frac{1.22\lambda}{A}$$

where θ is the apparent angular separation of the point objects (resolving power), λ the wave-length, and A the aperture, or diameter of the entrance pupil. For yellow light, the equation:

$$\text{Resolving Power} = \frac{4.5}{A}$$

gives the resolving power in seconds of arc when A is measured in inches. Thus the 200″ telescope has a *theoretical* resolving

power of 0.0225″. In large telescopes, the theoretical values are never attained, because of a limiting degree of perfection which can be achieved in the manufacture of the optical elements, and, more significantly, because of atmospheric disturbances which make for *poor seeing.*

412. Magnification

The resolving power of the eye is about 1½′. Unless the magnifying power of an instrument is sufficiently high to enlarge objects at the limit of resolving power of the telescope to this value, the full advantage is not realized. Therefore, the magnifying power should be, on this basis:

$$M = 20A$$

But this is really too strict a limitation, for the eye can realize a resolving power of 1½′ only under the best conditions. 3′ is a more practical figure, and this gives a *maximum* practicable magnifying power of 40 times the aperture in inches, which has proven a good rule.

Any magnification above this can only serve to ruin the definition by making the diffraction pattern of the point images visible. The lower the magnifying power, the better the definition, and it is well to keep it as low as possible without increasing the exit pupil over the value which can be readily utilized by the eye. If the diameter of the pupil of the eye is taken as ⅓″, we can write the *minimum* practicable magnifying power as

$$m = 3A$$

413. The Blue of the Sky

When a beam of white light encounters particles whose size is comparable to the wave-length of the light, the phenomenon of *scattering* occurs. The light whose wave-length is greater than the size of the particles will be nearly unhampered in its journey; the light whose wave-length is less than the size of

the particles will be reflected. The result is a selective action, by which longer wave-lengths are passed on and shorter wave-lengths are scattered in all directions.

This explains in part the color of the sky. The molecules of the gases composing the atmosphere scatter the shorter wave-lengths of sunlight, the blue and violet, and pass the longer wave-lengths unhindered. Thus the light which comes to our eye from a part of the sky distant from the sun represents the light which is scattered by the atmosphere. If this scattering did not take place, that is, if there were no atmosphere, the sky would be black and the stars would be visible in the day-time.

It might seem that the sky should be violet rather than blue, but it must be remembered that we are looking through a considerable depth of atmosphere and that along the path of our vision, additional scattering is taking place. The light we see is, therefore, the longer wave-length part of the originally scattered light, the violet being rescattered.

414. The Rainbow

When the air is saturated with water vapor, and the sun is low in the sky, we often have the phenomenon of the rainbow. This is the *spectrum* produced by dispersion of the light reflected from the water droplets along our line of sight *away from* the sun.

The light enters the droplets, is reflected from the rear surface, and emerges again, being dispersed both at entrance and exit. But the dispersion at the entrance affects the angle of incidence at the second surface to a large degree, owing to the sphericity of the droplet, so that the *deviation* of the red rays is greater than that of the violet (fig. 209).

When observing from O, our eye receives red rays from all the droplets along the line OB. Hence the rainbow appears with the red on the outside of the arch. The radius of the red arch

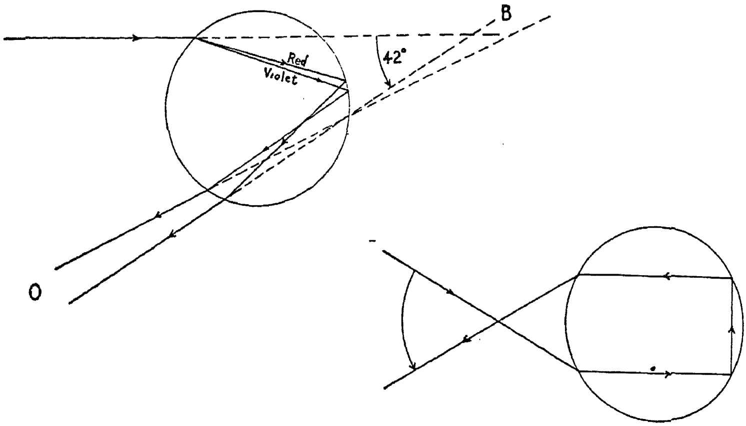


FIG. 209

Formation of the rainbow

is always the same value, 42°, and the center of curvature of the arch is along a line parallel to the direction of the sun.

Occasionally, a rainbow is formed by light which is reflected twice inside the droplets. This secondary bow appears outside the primary bow, and is reversed, the red appearing on the inside.

415. Mirages

Certain conditions in the atmosphere with respect to its variation in density may give rise to a certain type of mirage, where the light is bent as in fig. 210, so as to enter the eye in the apparent direction AO, when objects actually over the horizon appear in the sky. This occurs when the temperature of the atmosphere at higher levels is less than at lower levels. There is a layer of low density near the surface; this may reflect the sky light upward into the eye, thus giving a realistic impression of water.

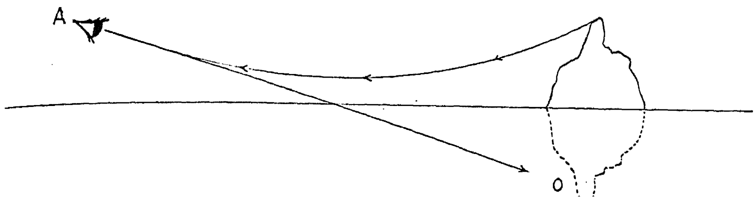


FIG. 210

Mirages

416. Optical Illusions

While it is not possible to enter into a theoretical discussion of optical illusions here, it may be mentioned that they depend principally upon deceiving the brain in its interpretation of the images formed on the retina, and in some cases upon the aberrational errors of the eye. The eye is by no means a well-corrected optical instrument. It has considerable chromatic aberration and distortion which are, in normal life, automatically corrected in the brain itself through the memory processes working on information gained by the other senses, but which are shown up in certain types of diagrams where the brain has no memory to work upon.

The existence and location of the blind spot of the eye can be easily noted by observing a prominent spot and then moving the gaze about until it disappears while objects farther from the center of fixation remain visible. To perform this test, select a prominent spot, then cover one eye and fix the gaze at a point about 15° toward the nose and slightly above the selected spot. Move the gaze about in this region until the spot disappears. This indicates that the blind spot, where the optic nerve leaves the eyeball, is about 15° toward the nose and slightly above the macula.

417. Photoelectric Effects

It was mentioned in (402) that certain phenomena in connection with light cannot be explained by the wave theory.

These are the *photoelectric effects.* Light, falling on a sensitive material, such as selenium, has the property of sending out electrons at considerable velocity. The number of electrons sent out depends upon the intensity of the light, but their velocity depends only upon the frequency. If the illumination is reduced to almost immeasurably small proportions, electrons are still sent out with the same velocity, and each electron originates, of course, from a certain atom, whereas the energy (considered in wave form) has been spread over a considerable area. Such a phenomenon can only be explained by a particle theory of light, which, however, cannot explain interference and diffraction.

Thus there are really two irreconcilable theories of light: wave and particle theory. The physicists have still been unable to combine the necessary features of the two into a usable single theory.

418. Polarized Light

Light waves are three-dimensional, that is, the vibration of the particles of the transmitting medium are in all possible directions perpendicular to the direction of the energy propagation. It is possible, however, to have light in which the direction of motion of the particles of the transmitting medium occur only in one plane, and such light is said to be *plane polarized.* Any beam of unpolarized light can be considered to be composed of a combination of two beams polarized at right angles to each other.

Certain materials, such as calcite, quartz, etc., have different refractive indices for light polarized in two mutually perpendicular planes, and their effect upon an unpolarized beam of light is to divide it into two components, each of which consists of light polarized in a particular plane, and each of which is refracted at the boundary in a different direction. Thus, in such materials, there are two refracted rays corresponding to a single unpolarized incident ray. These two

rays are denoted by the terms *ordinary* and *extraordinary*. In the case of perpendicular incidence, the extraordinary ray is actually bent away from the normal, while the ordinary ray proceeds according to the common principles of refraction.

The *optical axis* of such a double-refracting crystal is the direction along which the ordinary and extraordinary rays travel together at the same velocity, and, therefore, are not separated. Some materials are *biaxial,* possessing two optical axes, and in these, both ordinary and extraordinary rays behave in peculiar fashion.

419. The Nicol Prism

The most common device used in optical instruments for producing and analyzing polarized light is the Nicol prism (fig. 211). This consists of a double prism of calcite (Iceland spar), cut as indicated in the diagram. The dotted lines indicate the natural rhomb form of the crystal. The optical axis is perpendicular and in the plane of the diagram. The two prisms are cemented with Canada balsam, and the angles are such that the extraordinary ray is transmitted as shown, while the ordinary ray is totally reflected at the joining face. Two such prisms occurring in succession in an optical path will

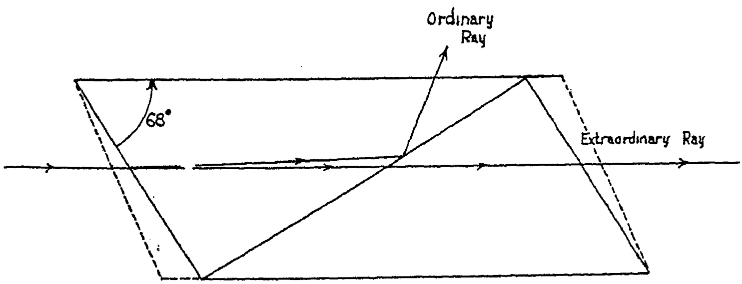


FIG. 211

The Nicol prism

transmit plane-polarized light or exclude all light according as their optical axes are parallel or perpendicular.

420. Polaroid

The crystals of iodo-sulfate of quinine have the property of transmitting plane-polarized light in a particular direction. Sheets of these crystals, treated by a method which lines up their optical axes parallel to one another, and then mounted between two thin sheets of plastic, form the material known as Polaroid, which has come into common use in recent years. Its polarization is not as complete as that of the Nicol prism, but it has become an extremely useful and economical component of optical instruments (269).

421. Optical Rotation

Certain substances have the property of rotating the plane of polarization of incident polarized light, and through this property provide a means for their detection and analysis by such instruments as the polarimeter (269) and the polarizing microscope (205). These materials may be either *left-* or *right-handed,* according to the direction in which the rotation occurs.

APPENDIX I

Mathematical Proofs

1. The Effect of a Wave at a Point (see 4)

Consider a plane wave, WW (fig. A) and a point, P, in advance of it. We will investigate the effect of the wave at

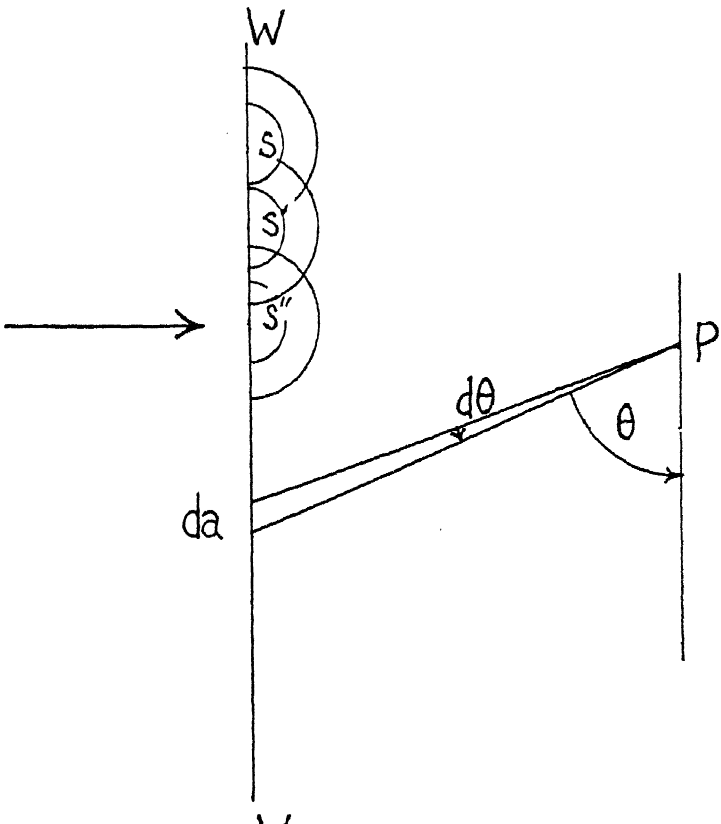


Fig. A

the point P. The wave theory of light states that any wave front, such as WW, may be considered to be an infinite series of point sources, is indicated by s, s′, s″, etc.

Consider a small element, da, of the wave front WW, and, where the total energy radiated by the entire wave front is I, let the amount radiated by the element da be dI. This is radiated in all directions, and in particular, that amount of radiation in the direction P will be dIdθ. The component in the original direction of propagation will be dI sin θ dθ.

Thus, the energy received at P from all elements da will be:

$$\int^{90} d\,I \sin\theta \, d\,\theta$$

or

$$-\,dI\left(\cos\frac{\pi}{2} - \cos 0\right) = dI \qquad \text{(i)}$$

But dI is the amount of energy which would have been received at P if the wave front WW had advanced to that point without giving rise to secondary wavelets. Therefore, the effect at P of the *infinite* wave front WW is the same as would be the effect of a vanishingly narrow ray traveling in the same direction as the wave disturbance.

2. The Law of Reflection (see 15)

Consider a plane wave, AB, approaching a plane reflecting surface, MM′, at an angle of incidence I (fig. B). At the surface, the wave will give rise to a series of secondary wavelets about points such as a_1, a_2, a_3., Now, the situation at the instant that the point B has advanced to B′ is that surrounding a point, say a_2, there is a secondary wavelet which has advanced a distance $a_2\,a''_2$, equal to $a_2\,a'_2$, the distance the wave front would have advanced if the reflecting surface MM′ had not been present.

Now a line perpendicular to the surface MM′ through a'_2 will be a chord of the circle about a_2, and will intersect the circle above the surface in the point a''_2. Therefore, a'_2 and a''_2 and, in

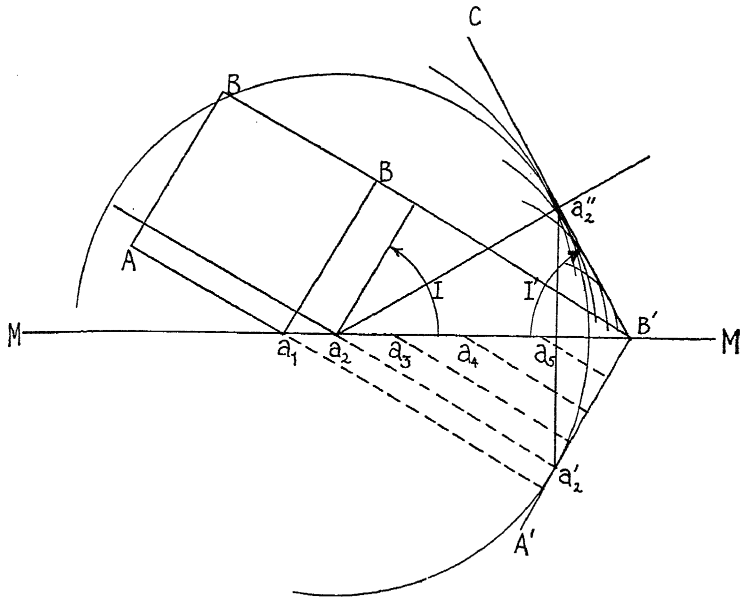


FIG. B

general, all points a′ and a″, will be symmetric about the surface MM′. Hence a line B′C which is tangent to all the secondary wavelets above the surface will be symmetric about MM′ with a line B′A′ which is tangent to all the circles below the surface, and $< I' = < I$. This, then, is the law of reflection:

$$I' = -I \tag{ii}$$

the negative sign being necessary because the sense of I′ is opposite to that of I.

3. The Image-Points in a Pair of Inclined Plane Mirrors Are Located on a Circle (see 17)

For every object-point, the image-point is symmetric about one of the mirrors. But every image-point for one mirror is an object-point for the other. Thus we have a series of pairs of points, symmetric alternately about two lines. But each pair can

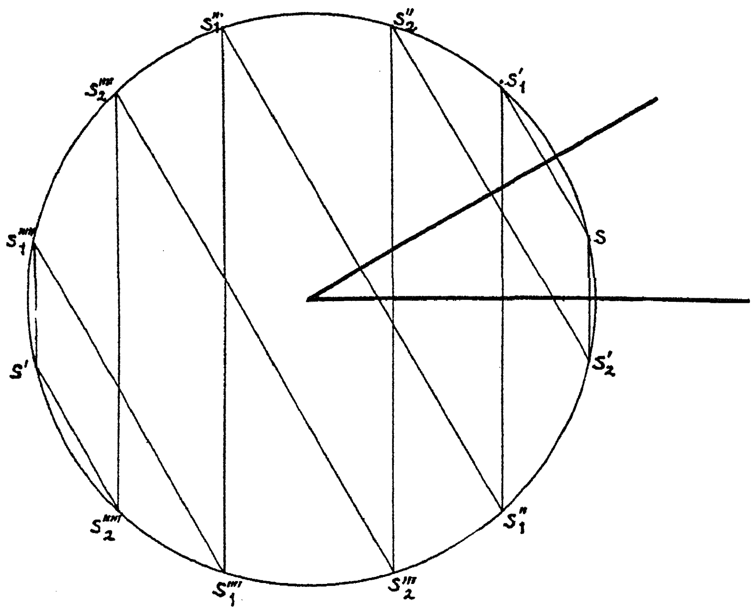


FIG. C

be considered to define the chord of a circle, of which the associated line is a radius. And these two lines intersect at the center of the circle.

When the two lines are inclined at 90° (fig. D) then a″ has the same relation to a whether it is constructed through a'_1 or through a_2. Thus, both constructions coincide at a″ and any further construction merely relocates existing points. Therefore, in two plane mirrors inclined at 90°, there are exactly three images produced.

4. The Law of Refraction (see 20)

Consider a plane wave AB approaching a plane refracting surface MM′ (fig. E). This wave will give rise to a series of wavelets at the surface about points such as a_1, a_2, a_3. At the instant when the point B of the wave has advanced to the

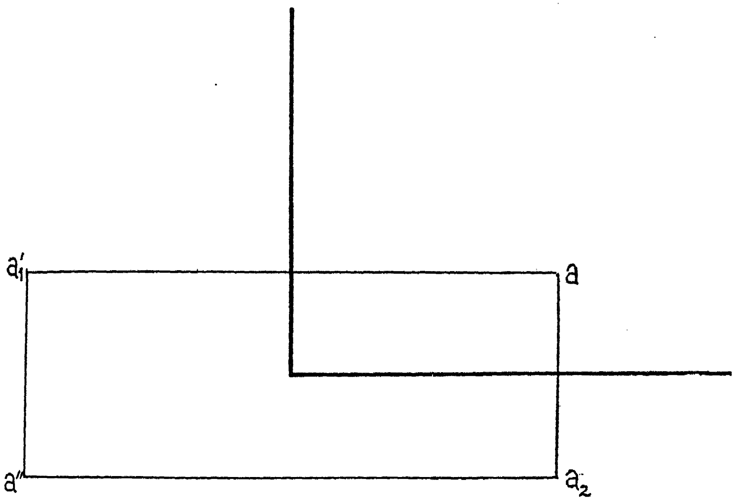


FIG. D

surface at B′, there is a secondary wavelet about a point, say a_2, which has advanced the distance $a_2a''_2$, equal to $a_2a'_2\frac{n}{n'}$, if a'_2 is the point to which the wave front would have advanced if the refracting surface MM′ were not present, n is the index of refraction (reciprocal of the velocity in terms of the velocity in a vacuum) of medium m, and n′ the index of refraction of medium m′.

Now, the radius aa″ of any secondary wavelet is directly proportional to the distance B′a, therefore, the envelope of the wavelets is a straight line.

Moreover:

$$\frac{\sin I}{\sin I'} \quad \frac{aa'}{aa''} \quad \frac{aa'}{aa'\frac{n}{n'}} \quad n \tag{iii}$$

or:

$$n \sin I = n' \sin I' \tag{iv}$$

and this is the law of refraction.

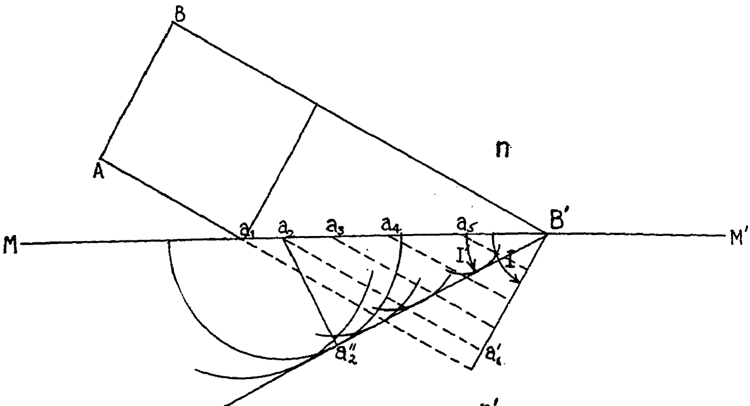


FIG. E

5. Paraxial Imagery in a Plane-Parallel Plate (see 35)

Given a plane-parallel plate (fig. F) and a point object located at s, the image of s in the first surface will be at s′ and the image of s′ in the second surface will be at s″.

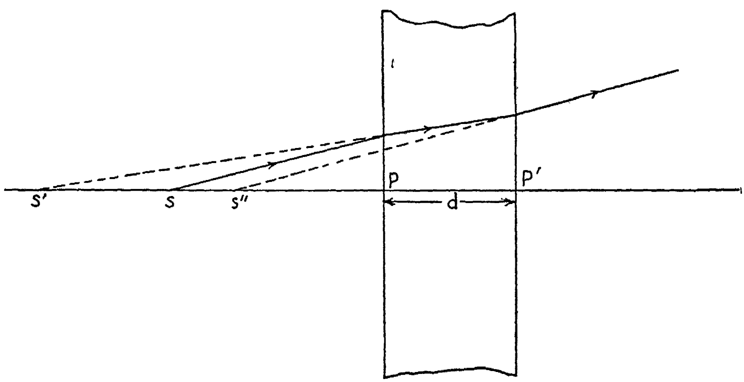


FIG. F

We can write, from the figure:

$$ss'' = sP - s''P = sP - s''P' + d \qquad (v)$$

But, from (31):

$$s''P' = \frac{n}{n'}\, s'P' = \frac{n}{n'}\,(s'P + d)$$

and:

$$s'P = \frac{n'}{n}\, sP$$

therefore:

$$s''P' = — \quad — sP + d$$

whence:

$$ss'' = sP - \frac{n}{n'}\left\{\frac{n'}{n}\, sP + d\right\} + d = sP - sP - \frac{n}{n'}\, d + d = d\left\{\frac{n' - n}{n'}\right. \qquad \text{(vi)}$$

6. Refraction Through a Prism (see 36, 37, 38, 39, 40)

Consider a prism (fig. G) of refracting angle A, and a ray entering the first face at an angle of incidence I_1. We shall use the conventions as to sign given in (41).

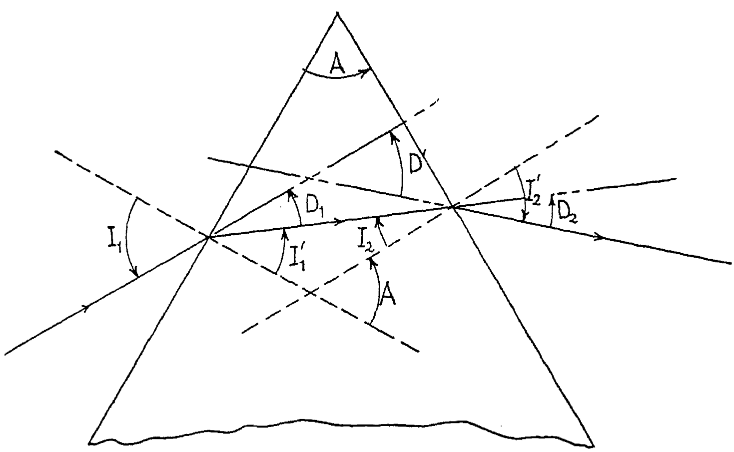


FIG. G

Now, if N is the relative index of refraction of the medium comprising the prism, we have, from the law of refraction:

$$\sin I'_1 = \frac{\sin I_1}{N}$$

$$\sin I'_2 = N \sin I_2$$

and, by inspection:

$$I_2 = I'_1 - A \qquad \text{(vii)}$$

where A is considered positive.

A. Direction of Deviation

Now, the aspect of sign will not change if we consider $I = \sin I$; hence we can write:

$$I'_1 = \frac{I_1}{N}$$

$$I'_2 = NI_2 \qquad \text{(viii)}$$

But the deviation by the prism is D, and we have:

$$D = (I_1 - I'_1) + (I_2 - I'_2) \qquad \text{(ix)}$$

or, since: $I_2 = I'_1 - A$ by (vii)

$$D = I_1 - I'_1 + I'_1 - A - I'_2 \doteq I_1 - I'_2 - A \qquad \text{(x)}$$

The deviation will be toward the base if D is positive, which will be true if:

$$I'_2 < I_1 - A$$

But, $I'_2 = NI_2 = N(I'_1 - A) = N\left\{\frac{I_1}{N} - A\right\} = I_1 - NA \qquad \text{(xi)}$

which will always be less than $I_1 - A$ if N is positive.

Therefore, the deviation by a prism (immersed in a lighter medium) will always be *toward the base.*

B. Minimum Deviation

Inspection of fig. G will show that the amount of deviation will depend upon the value of I_1 and that the variation will be continuous. Therefore, there will be one value of I_1 for which the deviation is a minimum, and associated with that will be a definite value of I'_2 on the emergent face.

But, if we reverse the direction of the incident ray, the conditions will be identical, and D will have the same value. But if the value of the original angle of incidence for minimum deviation for light incident from the left differs from the value for minimum deviation for light incident from the right, there will be two values corresponding to minimum deviation, and two values of D. This is impossible, and we are forced to the conclusion that, for minimum deviation, $I_1 = -I'_2$, and, moreover, that $I'_1 = -I_2$, from which it follows that $I'_1 = -I_2 = \frac{A}{2}$. Therefore, the ray which is least deviated by a prism is that ray which passes through the prism perpendicular to the bisector of the refracting angle (fig. H). This is called the *symmetric ray.*

C. Limiting Angle of Incidence

The condition for total reflection at the second face of the prism is $I_2 > C$, the critical angle for two media involved. The limiting value is:

$$I_2 = -C \qquad \text{(xii)}$$

But,

$$I_2 = I'_1 - A \text{ by (vii)}$$

and, combining with (xii) we have:

$$I'_1 = A - C \qquad \text{(xiii)}$$

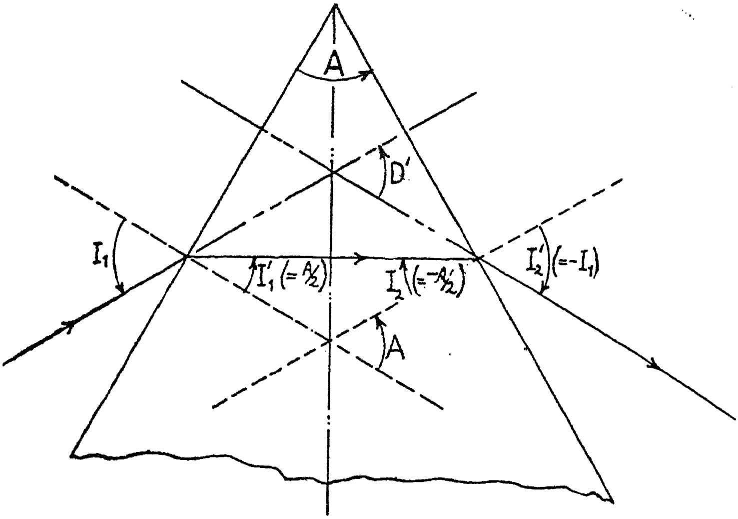


FIG. H

But,

$$\sin I'_1 = \frac{1}{N} \sin I_1$$

whence:

$$\sin I_1 = N \sin (A - C) \qquad \text{(xiv)}$$

D. Deviation of a Thin Prism

When the refracting angle A is small and the light is incident close to the normal, we can use radian values for the angles. We have, for the deviation of the prism, from (x):

$$d = i_1 - i'_2 - A$$

Now, in this case for a thin prism, the total deviation, d, will not be greatly different from the minimum deviation, for which $i'_2 = -i_1$ by (B), therefore:

$$d = 2i_1 - A \qquad \text{(xvi)}$$

But, in this case, $i_1 = Ni'_1 = N\dfrac{A}{2}$ by (B), wherefore:

$$d = NA - A = (N - 1)A \qquad \text{(xvii)}$$

7. **Paraxial Imagery in a Spherical Surface** (see 44, 48, 110)

Given a spherical reflecting surface, ZZ′ (fig. I) and an incident ray at P, we wish to develop equations for the path of the reflected ray.

We know the quantities r, U and OB = m in the figure, and wish to determine U′ and OB′ = m′.

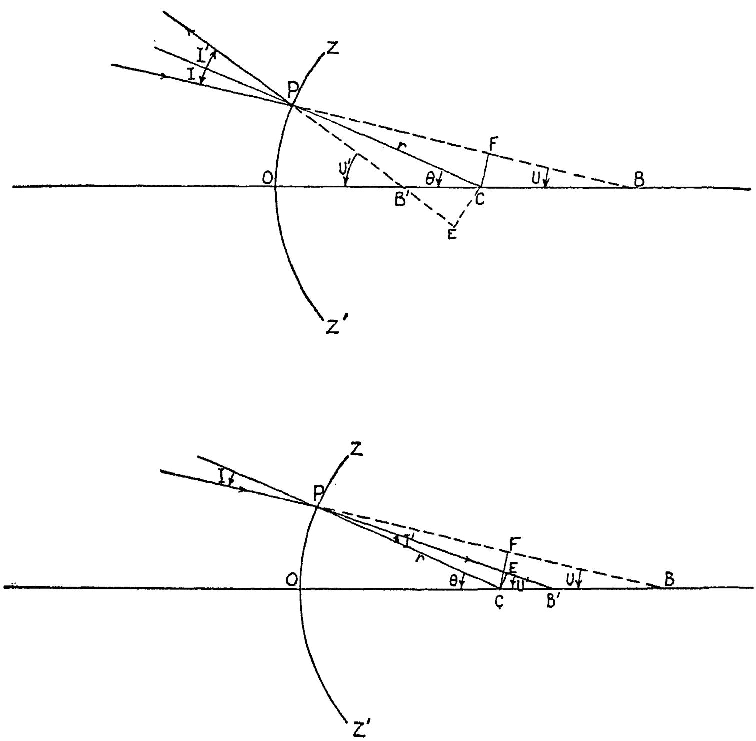


Fig. 1

Now, $\sin I = \dfrac{FC}{r}$ by inspection, and also $FC = CB \sin U$. But, $CB = m - r$, wherefore:

$$\sin I = \frac{(m - r)\sin U}{r} \qquad \text{(xviii)}$$

Now, by the law of reflection: $I' = -I$ (15)

And, by inspection: $U' = \theta - I'$

but, $\theta = U + I$

whence: $U' = U + I - I'$ (xix)

Also, we have $CB' = m' - r = \dfrac{EC}{\sin U'}$. But $EC = r \sin I'$, wherefore:

$$m' = \frac{r \sin I'}{\sin U'} + r \qquad \text{(xx)}$$

Now, if the angles, I, I′, U, and U′ are small, the radian values of these angles may be substituted for their sines, and we have, using the symbol conventions outlined in (32):

$$i = (m - r)u$$

$$i' = -i$$

$$u' = u + i - i' = u + 2i \qquad \text{(xxi)}$$

$$m' = \frac{ri'}{u'} + r$$

In the case of refraction, the construction will be identical, and in place of the law of reflection, $I' = -I$, we have the law of refraction, $n \sin I = n' \sin I'$. Wherefore, we can at once write:

$$\sin I = \frac{(m - r)\sin U}{r}$$

$$N \sin I = N' \sin I'$$

$$U' = U + I - I' \qquad \text{(xxii)}$$

$$m' = \frac{r \sin I'}{\sin U'} + r$$

and, for the paraxial case:

$$i = \frac{(m - r)u}{}$$

$$ni = n'i'$$

$$u' = u + i - i' \qquad \text{(xxiii)}$$

$$m' = \frac{ri'}{u'} + r$$

8. Linear Magnification (see 54)

We know from (44, 53) that, for the paraxial case at least, all rays emanating from a point, say q, of an object will meet at a point, q′, of the image. Thus, in fig. J, taking the ray from q incident at the vertex O of a spherical reflecting surface, ZZ′ we have, because $i' = -i$, the similar triangles bqO, b′q′O, from which:

$$\frac{b'q'}{bq} = \frac{b'O}{bO} \qquad \text{(xxiv)}$$

But,

$$bO = -m$$

$$b'O = m'$$

So:

$$\frac{b'q'}{bq} = -\frac{m'}{m} \qquad \text{(xxv)}$$

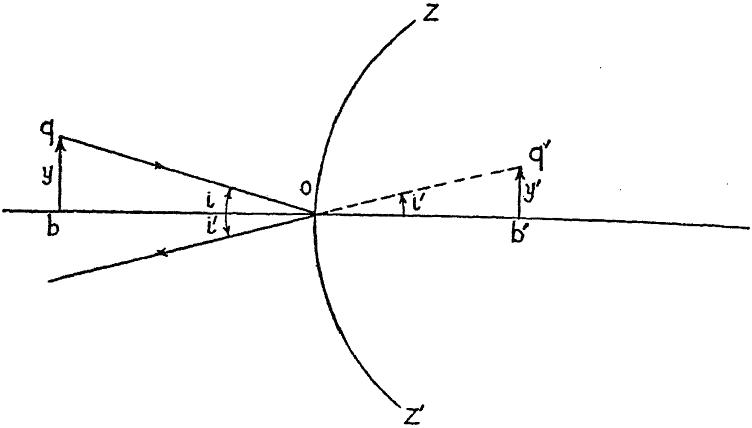


FIG. J

For a refracting surface (fig. K) the triangles are not similar, but the angles are paraxial, and we can write:

$$\frac{b'q'}{b'q''} \qquad \frac{i'}{i} = \frac{n}{n'} \qquad \text{(xxvi)}$$

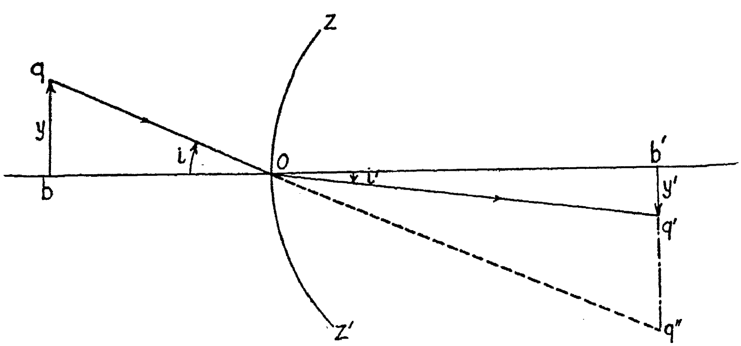


FIG. K

and, since: $$\frac{b'q''}{bq} \qquad \frac{m'}{m}$$

we have:

$$\frac{\frac{n'}{n}\, b'q'}{bq} = \frac{m'}{m}$$

so:

$$\frac{b'q'}{bq} = \frac{n}{n'}\,\frac{m'}{m} \qquad \text{(xxvii)}$$

9. **Optical Center of a Lens** (see 58)

If we consider the two parallel radii, C_1P_1 and C_2P_2 in fig. L, and consider the path of the ray between P_1 and P_2, we see that it crosses the axis at a point O, which can be

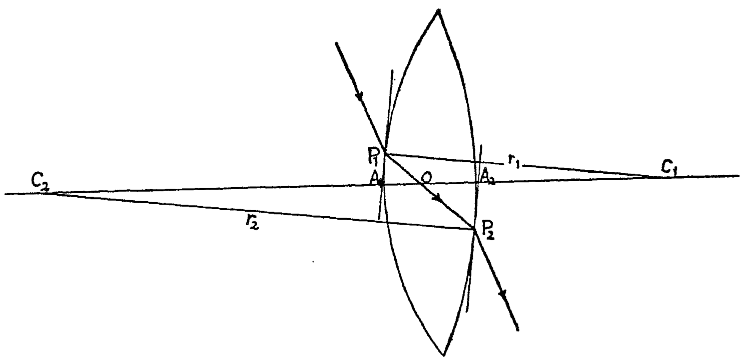


FIG. L

determined as follows:

$$\begin{array}{ccc} OC_1 & A_1C_1 & \\ OC_2 & A_2C_2 & r_2 \end{array}$$

since the angles at C_1 and C_2 are equal.

$$\begin{array}{cc} OC_1 + OA_1 & r_1 \\ OC_2 + OA_2 & r_2 \end{array}$$

Therefore:

$$\frac{OA_1}{OA_2} = \frac{r_1}{r_2} \qquad \text{(xxviii)}$$

But, $$OA_2 = d - OA_1$$

So: $$\frac{OA_1}{d - OA_1} = \frac{r_1}{r_2}$$

or $$OA_1 = d\,\frac{r_1}{r_1 - r_2} \qquad \text{(xxix)}$$

the negative sign being necessary because the radii are of opposite sign.

10. Image Equations Referred to the Principal Foci (see 61)

To refer the object and image distances to the principal foci, f and f′, instead of to the vertex, O, we have, from equation (9):

$$\frac{n'}{m'} - \frac{n}{m} = \frac{n' - n}{r}$$

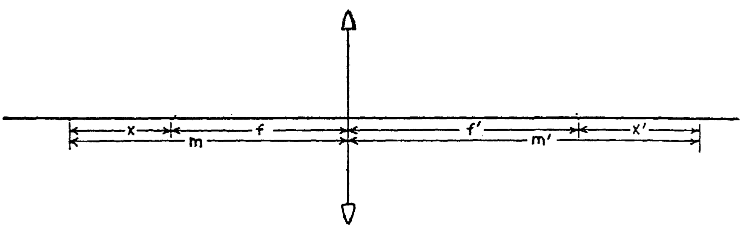


FIG. M

and since, by equation (11):

$$f' \qquad r \qquad \frac{n}{f}$$

we have:

$$\frac{n'}{m'} - \frac{n}{m} = \frac{n'}{f'} \qquad \text{(xxx)}$$

Now, putting

$$m' = x' + f'$$
$$m = x + f$$

we have:

$$\frac{}{x' + f'} \quad \frac{}{x + f} \quad : \frac{n'}{f'} \qquad \text{(xxxi)}$$

Removing fractions gives

$$n'f'(x + f) - nf'(x' + f') = n'(x' + f')(x + f)$$

and, expanding and collecting terms, we have:

$$-nf'x' - nf'^2 = n'x'x + n'x'f$$

Dividing by f gives:

$$nx'\frac{f'}{f} + nf'\frac{f'}{f} = -\frac{n'x'x}{f} - n'x' \qquad \text{(xxxii)}$$

But, $$\frac{f'}{f} \quad \cdot\frac{n'}{n}$$

by equation (11a), therefore:

$$ff' = x'x \qquad \text{(xxxiii)}$$

11. Principal Planes of a Thick Lens (see 71)

Restricting ourselves to the case of a thick lens of index of refraction N, surrounded by air, we have, for the two surfaces, from (71):

$$\begin{array}{ccc} \dfrac{N}{m'_1} & \dfrac{1}{m_1} & \dfrac{1}{f_1} \\ \dfrac{1}{m'_2} & \dfrac{N}{m_2} & \dfrac{1}{f'_2} \end{array} \qquad \text{(xxxiv)}$$

But, $$m_2 = m'_1 - d$$

where d is the thickness of the lens, and (xxxiv) becomes:

$$\frac{1}{m'_2} - \frac{N}{m'_1 - d} = \frac{1}{f'_2} \tag{xxxv}$$

Solving the two equations (xxxiv) and (xxxv) for m'_1, we obtain:

$$m'_1 = -\frac{Nf_1 m_1}{m_1 - f_1} \tag{xxxvi}$$

$$m'_1 = \frac{f'_2 d - m'_2 d + f'_2 m'_2 N}{f'_2 - m'_2} \tag{xxxvii}$$

Eliminating m'_1, expanding and collecting terms, we have:

$$m_1 m'_2[N(f'_2 - f_1) - d] - m'_2(Nf_1 f'_2 - f_1 d) + \\ + m_1(Nf_1 f'_2 + f'_2\, d) - f_1 f'_2 d = 0 \tag{xxxviii}$$

Now, we desire an equation of the *form:*

$$\frac{1}{m'_2 - \beta} - \frac{1}{m_1 - \alpha} = \frac{1}{F}$$

which may be written:

$$m'_1 m'_2 + m'_2(F - \alpha) - m_1(F + \beta) + F\alpha - F\beta + \alpha\beta = 0 \tag{xxxix}$$

Now, dividing (xxxviii) by the coefficient of $m_1 m'_2$, we have:

$$m_1 m'_2 - m' \frac{Nf_1 f'_2 - f_1 d}{N(f'_2 - f_1) - d} + m_1 \cdot \frac{Nf_1 f'_2 + f'_2 d}{N(f'_2 - f_1) - d} \\ \frac{f_1 f'_2 d}{N(f'_2 - f_1) - d} = 0 \tag{xl}$$

Equating like coefficients in (xxxix) and (xl) gives:

$$F - \alpha = -\frac{Nf_1 f'_2 - f_1 d}{N(f'_2 - f_1) - d} = \frac{f_1 d}{N(f'_2 - f_1) - d} -$$

$$\frac{Nf_1f'_2}{N(f'_2-f_1)-d} \qquad \text{(xli)}$$

$$F+\beta=-\frac{Nf_1f'_2+f'_2d}{N(f'_2-f_1)-d}=-\frac{f'_2d}{N(f'_2-f_1)-d}-\frac{Nf_1f'_2}{N(f'_2-f_1)-d} \qquad \text{(xlii)}$$

And, if we put:

$$F=-\frac{Nf_1f'_2}{N(f'_2-f_1)-d} \qquad \text{(xliii)}$$

we obtain:

$$\alpha=-\frac{f_1d}{N(f'_2-f_1)-d} \qquad \text{(xliv)}$$

$$\beta=-\frac{f'_2d}{N(f'_2-f_1)-d} \qquad \text{(xlv)}$$

12. Aperture and Field of View of an Optical System (see 93)

A. Diaphragm in Front of Lens

If the radius of the diaphragm is A_1 and the diameter of the lens is A_2, the separation of diaphragm and lens d, and the field of view θ (fig. N), we have, by inspection:

$$\tan\frac{\theta}{2}=\frac{A_2-A_1}{d} \qquad \text{(xlvi)}$$

B. Diaphragm Behind Lens

Using the same symbols as before, and adding a and b as shown in fig. O, we see from inspection:

$$\tan\frac{\theta}{2}=\frac{A_2}{b} \qquad \text{(xlvii)}$$

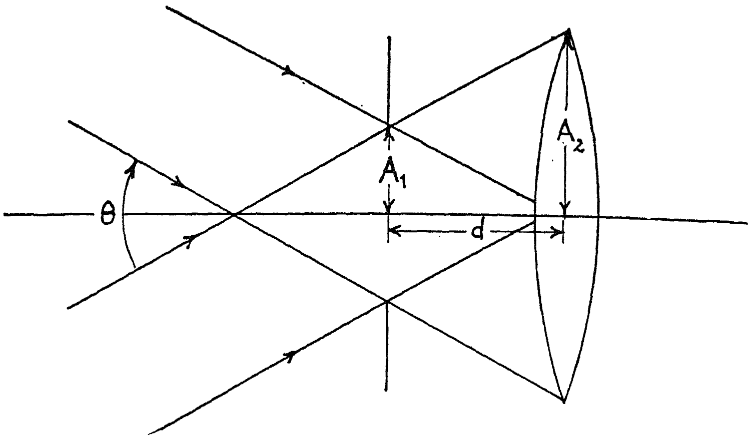


FIG. N

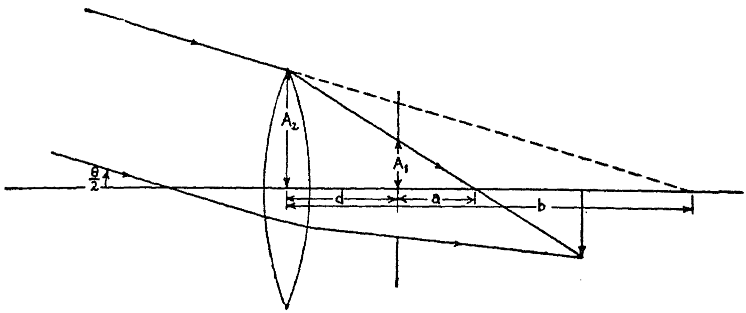


FIG. O

But, from equation (15):

$$\frac{1}{b} \qquad \frac{1}{d+a} - \frac{1}{f}$$

whence:

$$b = \frac{f(d+a)}{f+d+a} \tag{xlviii}$$

But, by inspection:

$$\frac{a}{d+a} = \frac{A_1}{A_2}$$

or

$$a = \frac{A_1 d}{A_2 - A_1}$$

Whence (xlviii) becomes:

$$b = \frac{A_2 f d}{A_2 f + A_2 d - A_1 f}$$

and, substituting this in (xlvii), we have:

$$\tan\frac{\theta}{2} = \frac{A_2 f + A_2 d - A_1 f}{fd}$$

which, upon simplification, becomes:

$$\tan\frac{\theta}{2} = \frac{A_2}{f} + \frac{A_2 - A_1}{d} \qquad \text{(xlvix)}$$

C. One Lens Serving as Diaphragm for Another

The diaphragm is assumed to be beyond the principal focus. Let the quantities be as shown in fig. P.

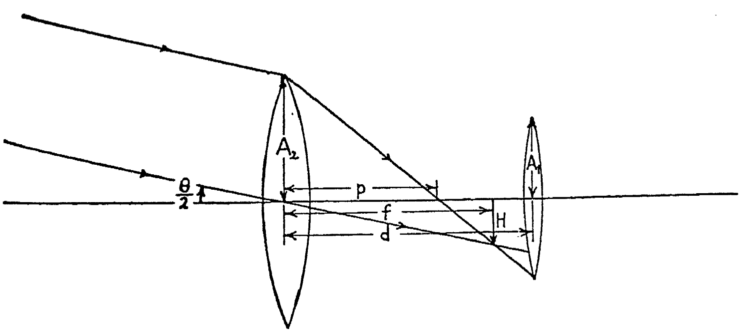


FIG. P

We can then write:

$$\tan\frac{\theta}{2} = \frac{H}{f} \qquad (1)$$

But, by inspection:

$$\frac{H}{f - p} = \frac{A_2}{p} \tag{li}$$

and

$$\frac{A_2}{p} = \frac{A_1}{d - p}$$

whence

$$p = \frac{A_2 d}{A_1 + A_2}$$

Substituting in (li), we have:

$$H = \frac{A_1 f}{d} + \frac{A_2 f}{d} - A_2 \tag{lii}$$

and, substituting in (l) gives:

$$\tan\frac{\theta}{2} = \frac{A_1}{d} + \frac{A_2}{d} - \frac{A_2}{f} = \frac{f(A_1 + A_2) - A_2 d}{fd} \tag{liii}$$

which can be transformed into solutions for A_1 and A_2 as follows:

$$\tan\frac{\theta}{2} = A_1\frac{1}{d} + A_2 \left(\frac{1}{d} - \frac{1}{f}\right)$$

Whence:

$$A_1 = \left\{\tan\frac{\theta}{2} - A_2\left(\frac{1}{d} - \frac{1}{f}\right)\right\} d = d\tan\frac{\theta}{2} + A_2\left(\frac{d}{f} - 1\right) \tag{liv}$$

$$A_2 = \frac{\tan\frac{\theta}{2} - \frac{A_1}{d}}{\frac{f - d}{fd}} = \frac{fd\tan\frac{\theta}{2} - A_1 f}{f - d} \tag{lv}$$

13. Chromatic Aberration

We have, from (105):

$$\frac{1}{f'_C} = (N_C - 1)c; \quad \frac{1}{f'_F} = (N_F - 1)c$$

Whence:

$$C = f'_C - f'_F = \frac{1}{(N_C - 1)c} - \frac{1}{(N_F - 1)c} \tag{lvi}$$

which becomes, upon simplification:

$$C = f'_C - f'_F = \frac{N_F - N_C}{(N_C - 1)\,(N_F - 1)c} \tag{lvii}$$

Now, the index of refraction, N_D, for a wave-length about midway between C and F, is not very different from either N_C or N_F, and we can, with close approximation, put:

$$(N_C - 1)\,(N_F - 1) = (N_D - 1)^2 \tag{lviii}$$

which gives us:

$$C = f'_C - f'_F = \frac{N_F - N_C}{c(N_D - 1)^2} \tag{lvix}$$

and, if we put f' as the focal length for wave-length D, we can write:

$$C = f'_C - f'_F = \frac{N_F - N_C}{N_D - 1} f'$$

But: $\dfrac{N_D - 1}{N_F - N_C} = V$ from (105),

therefore:

$$C = f'_C - f'_F = \frac{f'}{V} \tag{lx}$$

Now, for any thin lens, we have, for the focal lengths for two selected wave-lengths, say C and F:

$$\frac{1}{f'_{F_1}} = (N_{F_1} - 1)c_1$$

$$\frac{1}{f'_{C_1}} = (N_{C_1} - 1)c_1$$

$$\frac{1}{f'_{F_2}} = (N_{F_2} - 1)c_2 \qquad \text{(lxi)}$$

$$\frac{}{f'_{C}} = (N_{C_2} - 1)c_2$$

The focal lengths of these two lenses in contact will be:

$$\frac{1}{f_F} = \frac{1}{f'_{F_1}} + \frac{1}{f'_{F_2}} = (N_{F_1} - 1)c_1 + (N_{F_2} - 1)c_2;$$

$$\frac{1}{f_C} = \frac{1}{f'_{C_1}} + \frac{1}{f'_{C_2}} = (N_{C_1} - 1)c_1 + (N_{C_2} - 1)c_2 \qquad \text{(lxii)}$$

Now, if chromatic correction is to be attained, the two focal lengths must be equal, which requires that:

$$(N_{F_1} - 1)c_1 + (N_{F_2} - 1)c_2 = (N_{C_1} - 1)c_1 + (N_{C_2} - 1)c_2$$

or:

$$\frac{c_1}{c_1} = \frac{(N_{C_2} - 1) - (N_{F_2} - 1)}{(N_{F_1} - 1) - (N_{C_1} - 1)} = \frac{N_{C_2} - N_{F_2}}{N_{F_1} - N_{C_1}} = \quad \frac{N_{F_2} - N_{C_2}}{N_{F_1} - N_{C_1}} \qquad \text{(lxiii)}$$

Multiplying both sides by:

$$\frac{N_{D_1} - 1}{N_{D_2} - 1}$$

we have:

$$\frac{(N_{D_1}-1)c_1}{(N_{D_2}-1)c_2} \qquad \frac{N_{F_2}-N_{C_2}}{N_{F_1}-N_{C_1}} \cdot \frac{N_{D_1}-1}{N_{D_2}-1} \tag{lxiv}$$

and, substituting from (lxi) the focal length for the intermediate wave-length, D:

$$\frac{1}{f_D} = (N_D - 1)c$$

we obtain:

$$\frac{f_{D_2}}{f_{D_1}} \qquad \frac{V_1}{V_2} \tag{lxv}$$

14. The Paraboloidal Mirror (see 157)

A. Aplanatism

It is required to show that a parabola is a curve reflecting to the focal point all rays incident parallel to the axis. This will be true, in fig. Q, if the normal always bisects the angle formed by the incident ray and the line joining the point of incidence with the focus (Pf). This, it will be seen, requires only that $\phi = 2\theta$.

Knowing that:

$$\tan 2x = \frac{2 \tan x}{1 - \tan^2 x} \tag{lxvi}$$

we can write:

$$\tan 2\theta = \frac{2\tan\theta}{1-\tan^2\theta} : \frac{\dfrac{y}{p}}{1 - \dfrac{y^2}{4p^2}} = \frac{4py}{4p^2 - y^2} \tag{lxvii}$$

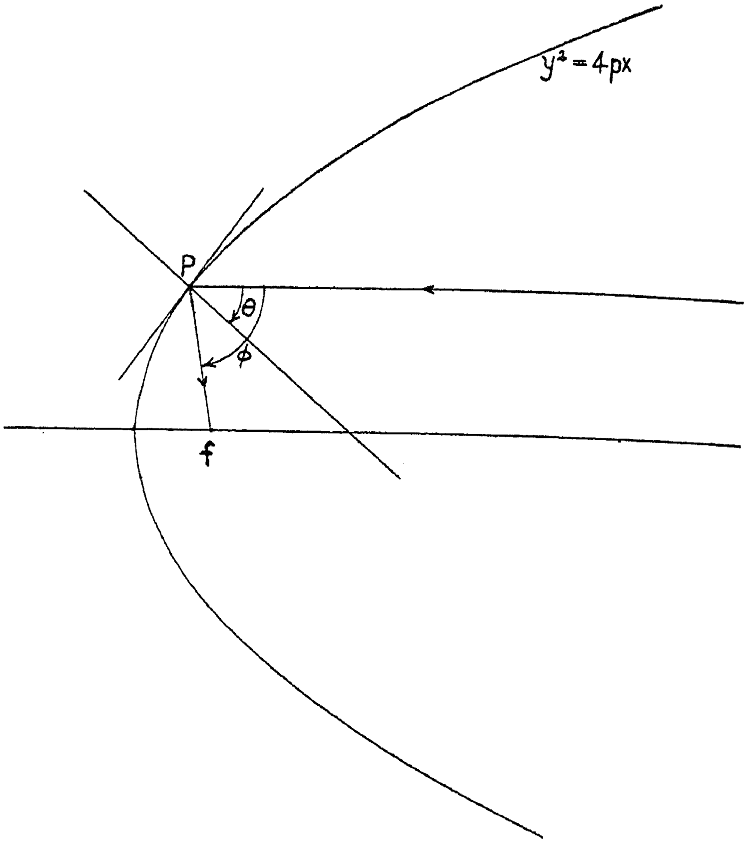


FIG. Q

and:

$$\tan\phi = \frac{y}{\dfrac{y^2}{4p} - p} = \frac{4py}{y^2 - 4p^2} \qquad \text{(lxviii)}$$

Therefore:

$$\phi = 2\theta \qquad \text{(lxix)}$$

B. Departure from a Sphere

Given a parabola and the circle which is tangent at the vertex (fig. R) we have:

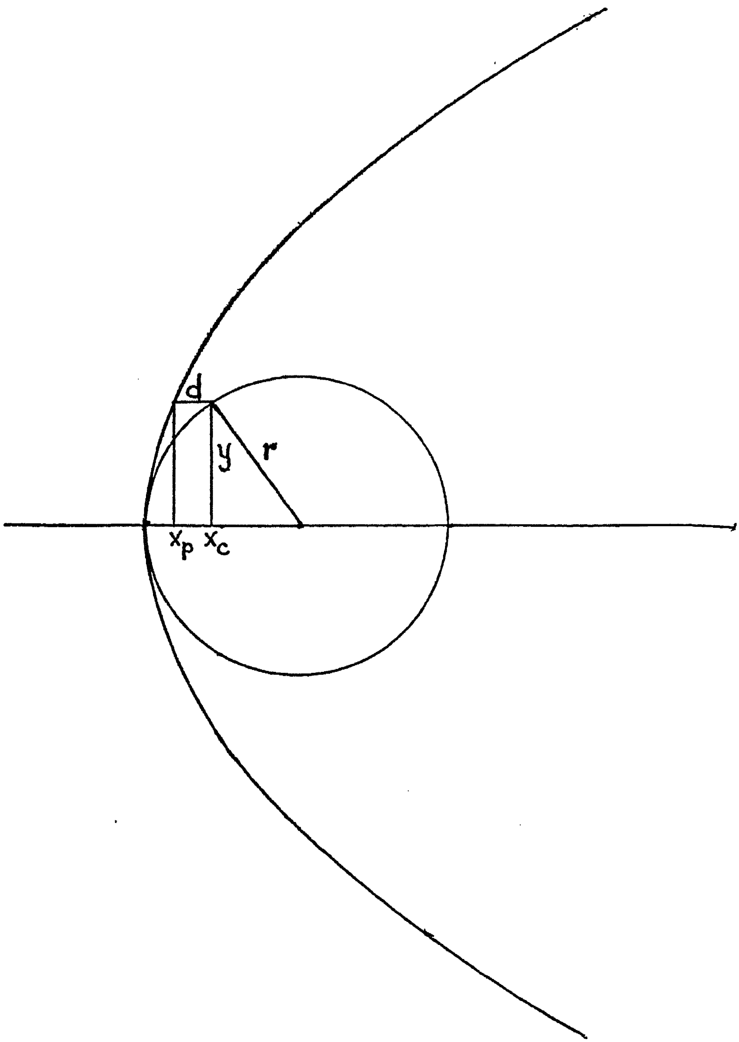


FIG. R

for the parabola:

$$y^2 = 2rx \tag{lxx}$$

and for the circle

$$(x - r)^2 + y^2 = r^2 \tag{lxxi}$$

Solving each for x gives:

$$x_p = \frac{y^2}{2r}$$

$$x_c = r - \sqrt{r^2 - y^2} \tag{lxxii}$$

and thus their separation in the x direction at a distance y from the axis is given by:

$$d = x_c - x_p = r - \sqrt{r^2 - y^2} - \frac{\quad}{2r} = \cdot \qquad \qquad 2r \tag{lxxiii}$$

Expanding in a power series gives, for the first term:

$$d = -\frac{y^4}{8r^3} + \cdots$$

15. Depth of Focus of a Lens (see 167)

Given a thin lens (fig. S), and an object at distance m, if we put x as the permitted diameter of the circles of confusion on a screen at the focal plane, there is a point at distance m_1

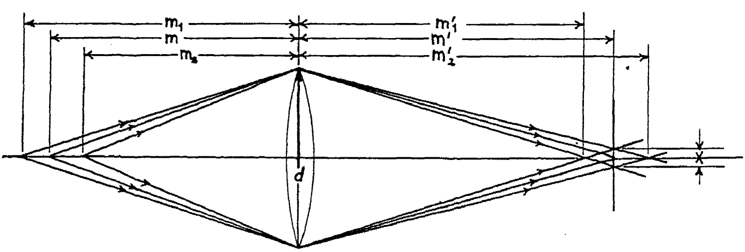


FIG. S

whose circle of confusion will be of diameter x at the focal plane. If we put d for the diameter of the lens, we can write:

$$\frac{x}{d} : \frac{m'}{m'_1}$$

therefore:

$$\frac{m'}{m'_1} = \frac{x}{d} + 1 = \frac{x+d}{d} \qquad \text{(lxxiv)}$$

But, from equation (15) we have:

$$\frac{1}{m'} - \frac{1}{m} = \frac{1}{f}$$

$$\frac{1}{m'_1} - \frac{1}{m_1} = \frac{1}{f} \qquad \text{(lxxv)}$$

From (lxxiv) we obtain:

$$\frac{1}{m'_1} = \frac{x+d}{m'd} \qquad \text{(lxxvi)}$$

and, substituting in (lxxv) we have:

$$\frac{x}{m'd} + \frac{1}{m'} - \frac{1}{m_1} = \frac{1}{f} \qquad \text{(lxxvii)}$$

which, upon combination with (lxxv) gives:

$$\frac{x}{m'd} - \frac{1}{m_1} = \frac{1}{f} - \frac{1}{m'} = -\frac{1}{m} \qquad \text{(lxxviii)}$$

Therefore:

$$m_1 = \frac{mm'd}{mx + m'd} \qquad \text{(lxxix)}$$

But,

$$t = m_1 - m = \frac{mm'd}{mx + m'd} - m \qquad \text{(lxxx)}$$

and therefore:

$$t = \frac{\quad}{mx + m'd} \tag{lxxxi}$$

Now, there is another point, nearer to the lens than the point at distance m, whose distance is m_2, which will give a circle of confusion at the focal plane whose diameter is x, and for this point we have:

$$\frac{x}{d} = 1 - \frac{m'}{m'_2}$$

whence:

$$\frac{m'}{m'_2} = 1 - \frac{x}{d} = \frac{d - x}{d} \tag{lxxxii}$$

But, from equation (15) we have:

$$\frac{1}{m'} - \frac{1}{m} = \frac{1}{f}$$

$$\frac{1}{m'_2} - \frac{1}{m_2} = \frac{1}{f} \tag{lxxxiii}$$

From (lxxxii) we obtain:

$$\frac{1}{m'_2} \quad \frac{d - x}{m'd} \tag{lxxxiv}$$

and, substituting in (lxxxiii), we have:

$$\frac{1}{m'} - \frac{x}{m'd} - \frac{1}{m_2} = \frac{1}{f} \tag{lxxxv}$$

which upon combination with (lxxxii) gives:

$$\frac{x}{m'd} \quad \frac{1}{m_2} \quad 1 \quad \frac{1}{m'} \quad \frac{1}{m} \tag{lxxxvi}$$

therefore:

$$m_2 = \frac{mm'd}{m'd - mx} \qquad \text{(lxxxvii)}$$

But,

$$t' = m - m_2 = m - \frac{mm'd}{m'd - mx} \qquad \text{(lxxxviii)}$$

and, therefore:

$$t' = -\frac{m^2x}{m'd - mx} \qquad \text{(lxxxix)}$$

APPENDIX II

Glossary of Optical Instrument Terms

ABBÉ PRISM: A prism designed by E. Abbé. It is a *roof* prism, inverting in two planes, and does not displace the axis.
ABERRATION: A condition in an optical system where image-points are imperfect or are improperly located (see CHROMATIC ABERRATION, SPHERICAL ABERRATION, DISTORTION, CURVATURE OF FIELD, COMA, ASTIGMATISM).
ABERRATION, CHROMATIC: See CHROMATIC ABERRATION.
ABERRATION, SPHERICAL: See SPHERICAL ABERRATION.
ABERRATION, TRANSVERSE CHROMATIC: See TRANSVERSE CHROMATIC ABERRATION.
ABERRATION, OBLIQUE: See OBLIQUE ABERRATION.
ABERRATION, SEIDEL: See SEIDEL ABERRATION.
ABSORPTION: The taking up of light energy by a substance.
ABSORPTION SPECTRUM: A spectrum produced by the absorption of specific wave-lengths of light from the radiation given out by a source which furnishes a continuous spectrum.
ACCOMMODATION: The adjustment of the lens of the eye, by means of the ciliary muscles, so that both near and far objects may be clearly seen.
ACHROMATIC: Without color. Corrected for achromatism.
ACHROMATIC LENS: A lens which has been corrected for chromatic aberration for two specific wave-lengths of light.
ACHROMATISM: The condition of being achromatic. The achievement of the achromatic condition.
ACHROMATISM, ASTROGRAPHIC: See ASTROGRAPHIC ACHROMATISM.
ADJUSTMENT: Putting in order. Correction.
ALTAZIMUTH MOUNTING: A telescope mounting providing for rotation about a vertical axis (azimuth) and about a horizontal axis (altitude).
ALTITUDE: The angular height of an object above a level line.

ALTITUDE, ANGLE OF: See ANGLE OF ALTITUDE.

AMICI PRISM: A prism designed by G. B. Amici. It is a *roof* prism, inverts in two planes, and deviates the light 90°.

AMMETROPIA: An abnormal condition of the eye, consisting of either near- or far-sightedness.

AMPLITUDE: The height of the crest of a wave above its zero, or midpoint.

ANALYZER: A device for determining the plane of polarization of a beam of light.

ANASTIGMAT LENS: A lens which is corrected for astigmatism.

ANASTIGMATIC: Free of astigmatism.

ANGLE, CRITICAL: See CRITICAL ANGLE.

ANGLE OF ALTITUDE: An angle measured in a vertical plane, beginning at a level line.

ANGLE OF AZIMUTH: An angle measured in a horizontal plane, beginning at the north point of the horizon, and measuring through east.

ANGLE OF DEVIATION: The angle between the paths of a light ray before and after passing the boundary of an optical medium.

ANGLE OF INCIDENCE: The angle between a ray of light approaching the boundary of an optical medium and the normal to that boundary at the point of contact.

ANGLE OF REFLECTION: The angle between a reflected light ray and the normal to the reflecting surface at the point of contact.

ANGLE OF REFRACTION: The angle between a refracted light ray and the normal to the refracting surface at the point of contact.

ANGLE, REFRACTING: See REFRACTING ANGLE.

ANGSTROM: A unit of measurement of wave-length, equal to 10^{-8} cm. or 0.00000001 cm.

ANGULAR MAGNIFICATION: Increase in the *apparent* size of an object by an optical system.

APERTURE: An opening. The optical projection of the aperture stop upon the objective.

APERTURE, NUMERICAL: See NUMERICAL APERTURE.

APERTURE STOP: That opening in an optical system or instrument which controls the size of the admitted bundle of

light. It may or may not be the cell containing the objective lens, and may be a diaphragm somewhere in the system.

APLANATIC: Free of spherical aberration and coma.

APLANATIC LENS: A lens which has been corrected for spherical aberration and coma.

APLANATIC POINTS: That pair of points for which a given optical system gives no spherical aberration or coma. The aplanatic points are conjugate focal points.

APLANATISM: The condition of being aplanatic.

APOCHROMATIC LENS: A lens which has been corrected for three specific wave-lengths of light. It usually contains three different kinds of glass.

AQUEOUS HUMOR: A transparent liquid which fills the space between the cornea and the lens of the eye.

ASPHERIC: Not spherical.

ASTIGMATIC: Exhibiting astigmatism.

ASTIGMATISM: That aberration which results in an object-point being rendered in its image as two mutually perpendicular lines, at different distances from the optical system. A defect of the human eye, resulting from unsymmetric curves on the cornea.

ASTROGRAPHIC ACHROMATISM: Achromatism which results in the minimum focus occurring in the blue-violet region of the spectrum, desirable for astronomical photography.

ASTROGRAPHY: Astronomical photography.

ASTRONOMICAL TELESCOPE: A telescope intended for use in observing celestial objects. It does not contain an erecting system.

AUXILIARY AXIS: An optical axis other than the principal axis, drawn for the purpose of exhibiting oblique aberrations.

AXIAL: Pertaining to the principal axis.

AXIAL PENCIL: That pencil of light rays which is symmetric about the principal axis.

AXIS, AUXILIARY: See AUXILIARY AXIS.

AXIS, MECHANICAL: See MECHANICAL AXIS.

AXIS OF ROTATION: That axis about which a device rotates.

AXIS, OPTICAL: See OPTICAL AXIS.

AXIS, PRINCIPAL: See PRINCIPAL AXIS.

AZIMUTH: The value of the angular position of an object in a horizontal plane, measured from the north point, through east.

AZIMUTH, ANGLE OF: See ANGLE OF AZIMUTH.

BACKLASH: Looseness in the teeth of a gear mechanism, permitting movement of one or more of the gears without corresponding movement in the connected mechanisms.
BALL AND SOCKET: A device for permitting rotation of a part in all planes.
BENCH, OPTICAL: See OPTICAL BENCH.
BIFOCAL: A term applied to spectacles which have two different lenses ground on one piece of glass, one lens on the lower part and another on the upper part, used in the correction of presbyopia.
BINOCULAR: Having two eyepieces.
BINOCULAR COLLIMATION: The adjustment of a binocular instrument so that the lines of sight of the two telescopes are parallel.
BINOCULAR INSTRUMENT: An instrument having two eyepieces, being adapted for simultaneous vision with both eyes.
BINOCULAR MICROSCOPE: A microscope adapted for simultaneous vision with both eyes. There is only one objective.
BRASHEAR-HASTINGS PRISM: A *roof* type prism, developed by Brashear and Hastings. It inverts in two planes but does not turn or displace the optical axis.
BRIGHT-LINE SPECTRUM: A spectrum consisting of a series of bright lines. Such a spectrum is given off by the incandescent vapors of the chemical elements.
BROKEN-CONTACT LENS: An achromatic lens where the two components are separated by a small air space.
BUNDLE: In optics, a collection of light rays, all pertaining to a given object- or image-point.
BUNDLE, OBLIQUE: See OBLIQUE BUNDLE.

CALCITE: Iceland spar. Calcium carbonate ($CaCO_3$).
CALIBRATION: Determination of proper scale markings.
CAMERA: An optical instrument for the purpose of taking pictures.
CAMERA, PINHOLE: A camera made from a light-tight box with a pinhole in one of the sides.
CAMERA, SCHMIDT: An astronomical camera of special type, consisting of a spherical mirror and a correcting plate.
CASSEGRAINIAN TELESCOPE: That form of the reflecting telescope which consists of a paraboloidal primary mirror and a hyperboloidal convex secondary mirror.

CELESTIAL EYEPIECE: A name sometimes given to ordinary eyepieces, because they are generally used for celestial observations.

CELL: A device for holding a lens or mirror.

CEMENTED LENS: A lens consisting of more than one component cemented together in a solid unit.

CENTERING: The process of grinding a lens concentric with its optical axis.

CENTER LENS: The middle component of a three-component eyepiece.

CENTER OF FIXATION: That point toward which the eye is directed.

CENTER OF ROTATION: That point about which the eyeball rotates.

CENTER, OPTICAL: See OPTICAL CENTER.

CENTIMETER: A unit of linear measurement, equal to one hundredth of a meter. (1 in. = 2.54 cm.)

CHARACTERISTIC FOCAL LINE: The short line which represents the convergence of an oblique bundle of rays from an extra-axial object-point.

CHORIOID: A thin black coating covering the inside of the eyeball just beneath the retina.

CHROMATIC ABERRATION: That aberration due to the dispersion of a lens which results in different wave-lengths of light converging at different distances from a refracting surface.

CILIARY MUSCLE: The muscle controlling the curvature of the lens of the eye.

COLLECTIVE LENS: A converging lens, usually a plano-convex lens, forming part of the objective system of a telescope, whose function is to flatten the field and to slightly increase the angular field of view.

COLLIMATING TELESCOPE: A telescope used for adjusting an optical instrument. Its optical and mechanical axes are made coincident.

COLLIMATION: The process of lining up the optical elements of an instrument.

COLLIMATION, BINOCULAR: See BINOCULAR COLLIMATION.

COLLIMATOR: A fixture, consisting of a reticle and a projection lens, used for adjusting an optical instrument.

COLLIMATOR SIGHT: A type of artillery or gun sight. It consists of a reticle and projection lens, producing an image of the reticle against the background of the target.

COLORIMETER: An instrument which is used for the measurement of the color absorption of a given substance for the purpose of determining its constitution.

COMA: That aberration of an oblique image-point due to the unsymmetrical deformation of the image.

COMPARATOR: An instrument used for the purpose of making precise measurements.

COMPARISON SPECTRA: Spectra produced from a laboratory source superimposed on the photograph of an unknown spectrum for the purpose of determining the wave-lengths of the lines composing the latter.

COMPASS: An instrument for indicating the direction of north. Magnetic compasses indicate magnetic north, gyroscopic compasses indicate true north.

COMPENSATING EYEPIECE: An eyepiece sold for use in microscopes which is especially corrected to compensate for the residual aberrations of apochromatic objectives.

COMPOUND EYEPIECE: An eyepiece consisting of more than one lens.

COMPOUND MICROSCOPE: A microscope consisting of two separate optical systems, objective and eyepiece.

COMPOUND TELESCOPE: A telescope consisting of three separate optical systems, objective, erecting system, and eyepiece.

CONCAVE: Curved inward. Hollow.

CONCENTRIC LENS: A lens the centers of curvatures of both surfaces of which are coincident.

CONDENSER: An optical device for concentrating light at a given point.

CONDENSER, DARK FIELD: A microscope condenser which casts light *across* the field of view.

CONDITION, SINE: A mathematical condition regarding the sines of the incident and refracted angles which is of great value in determining the state of an optical system with respect to the oblique aberrations.

CONE: The geometrical surface produced by the revolution of a line about an axis not parallel with itself.

CONJUNCTIVA: The thin transparent covering of the eyeball which contains the nerve endings and protects the cornea from dust and dirt.

CONSTANT-DEVIATION PRISM: A prism whose deviation is independent of the angle of incidence.

CONTACT LENS: A corrective lens for the human eye which is fitted snugly to the eyeball over the cornea.

CONTINUOUS SPECTRUM: A spectrum where all wavelengths are represented in a continuous sequence.

CONTOUR PROJECTOR: An optical instrument used for the projection of magnified images of the profiles of mechanical parts for comparison with a template or drawing.

CONVERGING LENS: A lens which converges light.

CONVERGING LIGHT: A beam of light in which the paths of the separate rays converge toward a point.

CONVEX: Bulging.

CORNEA: That part of the eyeball through which light enters the eye.

CORRECTED LENS: A lens which has been designed to give specified effects with respect to aberrations.

CORRECTING LENS: A lens, found in range finders, whose purpose is to equalize the focal lengths of the two objectives by forming a compound objective with the one of longer focal length.

CORRECTION: The removal of faults or errors from an optical system by proper design of components.

CRITICAL ANGLE: That angle which determines whether a ray of light will be reflected or refracted. Its sine is equal to the reciprocal of the index of refraction.

CROWN GLASS: A type of optical glass, low in dispersion and usually low in refractive index.

CULLET: Rejected optical glass from a previous batch, added to the next batch to promote ready melting.

CURVATURE: Strictly, the reciprocal of the radius of a curved surface.

CURVATURE OF FIELD: That aberration resulting from the fact that the focal surface of an optical system is usually not a plane, but is curved.

CYLINDRICAL LENS: A lens whose one or both surfaces are a portion of a cylinder.

CYSTOSCOPE: An optical instrument for the examination of the interior of the human body.

DARK-FIELD CONDENSER: See CONDENSER, DARK FIELD.

DARK-LINE SPECTRUM: See SPECTRUM, DARK LINE.

DECLINATION: The angular difference between true north and the direction indicated by a compass. One of the co-ordinates used for locating heavenly bodies; it represents the distance north or south of the celestial equator.

DEFINITION: In optics, the quality of an image with respect to the rendition of fine detail.

DENSITY: Weight per unit volume.

DEPTH OF FOCUS: That range of distances over which a clear image can be attained at a given setting of the focusing device of an instrument.

DEVIATION, ANGLE OF: See ANGLE OF DEVIATION.

DEVIATION PRISM: A prism designed for the purpose of deviating a beam of light.

DIAPHRAGM: A thin disk with central hole, placed in an optical system. The term may be used to describe any part which has the effect of a limited opening to light.

DIAPHRAGM, ANTIGLARE: A diaphragm placed in an optical system for the purpose of preventing extraneous light from reaching the image.

DIAPHRAGM, IRIS: An adjustable diaphragm, where the diameter of the opening may be varied.

DIFFRACTION: A term applied to that class of light phenomena which demonstrate its wave character.

DIFFRACTION GRATING: A device, consisting of a series of very fine straight lines ruled upon a suitable surface, for the purpose of producing spectra by means of interference.

DIOPTER, DIOPTRY: A unit of measurement of refracting power. It is equal to the reciprocal of the focal length in meters.

DIOPTER SCALE: A scale sometimes found on focusing eyepieces, indicating the refracting power of an instrument for a given setting of the eyepiece.

DIOPTRIC POWER: Refracting power.

DISPERSION: The phenomenon of color separation during refraction, due to the variation of the index of refraction with wave-length.

DISPLACEMENT PRISM: A prism designed for the purpose of displacing the optical axis of an instrument parallel to itself.

DISSECTING MICROSCOPE: A name sometimes applied to

the stereoscopic microscope, because of its common use in dissection.

DISTANCE, INTERPUPILLARY: See INTERPUPILLARY DISTANCE.

DISTORTION: That aberration of an image resulting in the incorrect geometrical representation of the object, extra-axial image-points are either too near to, or too far from, the center.

DIVERGING LENS: A lens which diverges light. It is thicker at the edge than at the center.

DIVERGING LIGHT: Light which is radiating from or as if from a point.

DOUBLE CONCAVE LENS: A lens both of whose surfaces are concave.

DOUBLE CONVEX LENS: A lens both of whose surfaces are convex.

DOUBLE VISION: That maladjustment of a binocular instrument in which the two lines of sight are not parallel, and the observer sees two separate images of the field of view superimposed but not coincident.

DOUBLET LENS: A lens consisting of two separated components, either or both of which may be compound.

DOVE PRISM: A prism, designed by Dove, which inverts in one plane and does not change the direction of light. It is essentially a right angle prism used in a particular way.

EFFECT, PHOTO ELECTRIC: See PHOTO ELECTRIC EFFECT.

EFFECT, STEREOSCOPIC: See STEREOSCOPIC EFFECT.

ELBOW TELESCOPE: A telescope in which the optical axis contains a right-angle bend.

ELECTROMAGNETIC SPECTRUM: The collection of radiation of various types with the same character as light, including X-rays, ultraviolet, infrared, heat, and radio waves.

ELEMENT, OPTICAL: See OPTICAL ELEMENT.

EMISSION SPECTRUM: See SPECTRUM, EMISSION.

EMMETROPIA: That condition of the human eye in which the near and far points are located in normal position. Freedom from ammetropia.

ENDPLAY: The condition, in a shaft or bearing, in which the shaft is permitted to move endwise.

ENTRANCE PUPIL: In an optical system, that opening (real or virtual) which represents the common base of all the cones of rays entering the instrument.

EPIDIASCOPE: A name applied to the opaque projector.

EQUATORIAL MOUNTING: A telescope mounting so arranged that one of its axes is parallel to the axis of the earth.

EQUIVALENT FOCAL LENGTH: For a given lens or optical system, the focal length of a thin lens which would produce a similar image.

ERECT: Upright, as an image in upright position. To make an image upright.

ERECTING LENS: A lens used for the purpose of erecting an image.

ERECTING PRISM: A prism used for the purpose of erecting an image.

ERECTING SYSTEM: A subsidiary optical system in an instrument, used for the purpose of erecting an image.

ERECTING SYSTEM, LENS: An erecting system composed of lenses.

ERECTING SYSTEM, PORRO PRISM: An erecting system devised by M. Porro, consisting of two right-angle prisms.

ERECTING SYSTEM, PRISM: An erecting system composed of prisms.

ERECTING SYSTEM, SYMMETRIC: A lens erecting system, consisting of two similar lenses, so placed that the light between them is in parallel bundles.

ERECTOR: A lens which is part of an erecting system.

EXIT PUPIL: In an optical system, that opening (real or virtual) which represents the common base of all the cones of light emerging from the system.

EXTRA-AXIAL: Away from the optical axis; pertaining to bundles of light at an angle to the optical axis.

EYE LENS: See LENS, EYE.

EYEPIECE: A subsidiary optical system designed for the purpose of adapting light to the eye so that an image can be examined at close range.

EYEPIECE, CELESTIAL: A term often applied to ordinary eyepieces when they are supplied for use on celestial objects with a telescope which normally uses a terrestrial eyepiece.

EYEPIECE, COMPENSATING: An eyepiece frequently fur-

nished for use with apochromatic microscope objectives. It has special corrections for the residual aberrations of the apochromatic objectives.

EYEPIECE, COMPOUND: An eyepiece consisting of more than one lens.

EYEPIECE, FOCUSING: An eyepiece held in an adjustable mounting, for the purpose of adjusting the focus of an instrument.

EYEPIECE, FRENCH: A type of eyepiece used by French designers on military instruments, consisting of a single field lens and a triple eye lens.

EYEPIECE, HUYGENIAN: An eyepiece designed by Huygens, consisting of two plano-convex lenses mounted with their convex sides facing the objective.

EYEPIECE, INVERTING: A name sometimes applied to ordinary eyepieces when they are furnished with a telescope which normally uses a terrestrial eyepiece.

EYEPIECE, KELLNER: An eyepiece similar to a Ramsden eyepiece, except that the eye lens is an achromatic lens.

EYEPIECE, NEGATIVE: An eyepiece where the real image is formed between the two lenses. The Huygens eyepiece is of this type.

EYEPIECE, ORTHOSCOPIC: An eyepiece especially corrected for distortion. It usually consists of a triple field lens and a single eye lens.

EYEPIECE, POSITIVE: An eyepiece in which the real image is formed outside the eyepiece, and which can be used as a magnifier.

EYEPIECE, RAMSDEN: An eyepiece designed by Ramsden, consisting of two plano-convex lens, mounted with their convex sides toward each other.

EYEPIECE, SIMPLE: An eyepiece consisting of a single lens.

EYEPIECE, SYMMETRIC: An eyepiece consisting of two similar lenses, usually both achromatic, used when a long eye distance is required.

EYEPIECE, TERRESTRIAL: An eyepiece containing an erecting system in addition to the usual eyepiece lenses.

FAR POINT: That point upon which the eye is focused when accommodation is relaxed. Normally, it is infinity.

FAR SIGHTEDNESS: That condition in the human eye in

which the near point is at a distance greater than normal. Hyperopia.

FIELD: See FIELD OF VIEW.

FIELD, CURVATURE OF: See CURVATURE OF FIELD.

FIELD GLASS: A compact binocular telescope, usually of the Galilean type.

FIELD LENS: That lens of a compound eyepiece which is nearest the objective.

FIELD OF VIEW: The angular extent of the object space represented in the image given by an optical instrument.

FIELD STOP: A diaphragm inserted in an optical system for the purpose of limiting the field of view.

FIGURING: The process of hand polishing on an optical surface to produce a more correct "figure" or shape to the surface.

FILTER: A sheet of glass or other material of limited transparency (either neutral or colored) used to control the quantity or quality of light permitted to enter the final image.

FINDER, RANGE: See RANGE FINDER.

FINING: The removal of bubbles for an optical glass melt by stirring.

FIXATION, CENTER OF: See CENTER OF FIXATION.

FLINT GLASS: A certain type of optical glass, containing lead oxide.

FLUORITE: Calcium fluoride (CaF_2).

FOCAL LENGTH: The distance from a lens to the point where it will form an image of an infinitely distant object.

FOCAL LENGTH, EQUIVALENT: See EQUIVALENT FOCAL LENGTH.

FOCAL LINE, CHARACTERISTIC: See CHARACTERISTIC FOCAL LINE.

FOCAL PLANE: The plane in which a real image is formed.

FOCAL POINT: The point where a focus is formed, usually of an infinitely distant object-point.

FOCUS: A point where light is converged by a lens or mirror. To bring light together at a point. To adjust an instrument for clear vision.

FOCUS, DEPTH OF: See DEPTH OF FOCUS.

FOCUS, MARGINAL: See MARGINAL FOCUS.

FOCUS, PARAXIAL: See PARAXIAL FOCUS.

FOCUS, PRINCIPAL: See PRINCIPAL FOCUS.

FOCUS, SAGITTAL: See SAGITTAL FOCUS.

FOCUS, TANGENTIAL: See TANGENTIAL FOCUS.
FOCUSING EYEPIECE: See EYEPIECE, FOCUSING.
FOVEA CENTRALIS: That part of the human eye where most distinct vision occurs.
FRAUNHOFER LINES: The dark absorption lines in the sun's spectrum which were observed and designated by Fraunhofer.
FRENCH EYEPIECE: See EYEPIECE, FRENCH.
FREQUENCY: In light, the number of vibrations per second.
FRONT-SURFACED MIRROR: A mirror with the reflecting coat on the front surface.

GEOMETRICAL OPTICS: That part of the science of optics which treats of the geometrical character of light rays.
GALILEAN TELESCOPE: See TELESCOPE, GALILEAN.
GLASS, CROWN: See CROWN GLASS.
GLASS, FIELD: See FIELD GLASS.
GLASS, FLINT: See FLINT GLASS.
GLASS, JENA: See JENA GLASS.
GLASS, OPTICAL: See OPTICAL GLASS.
GRATING, DIFFRACTION: See DIFFRACTION GRATING.
GREGORIAN TELESCOPE: See TELESCOPE, GREGORIAN.

HORIZONTAL TRAVEL: Rotation of an instrument in a horizontal plane.
HOUR ANGLE: Concerning the position of a heavenly body, its angular distance from the meridian.
HUYGENIAN EYEPIECE: See EYEPIECE, HUYGENIAN.
HYPERMETROPIA: See HYPEROPIA.
HYPEROPIA: Far sightedness.
HYPERTROPIA: See HYPEROPIA.

ILLUMINATION: Quantity of light present in an image or passing through an instrument.
ILLUMINATOR: A device for illuminating the slide of a microscope.
ILLUMINATOR, VERTICAL: See VERTICAL ILLUMINATOR.
IMAGE: A representation of an object by means of light rays, produced by an optical system. A cone of light originating at each object-point is converged at the image-point.

IMAGE MEDIUM: The medium containing the image.
IMAGE PLANE: The plane in which an image is formed.
IMAGE-POINT: The point where a cone of rays is focused by an optical system to form an image of an object-point.
IMAGE, REAL: See REAL IMAGE.
IMAGE SPACE: The space which is associated with an image, or space from which an image is viewed. If the image is virtual, it may not be located in the medium from which it is observed.
IMAGE, VIRTUAL: See VIRTUAL IMAGE.
INCIDENCE: Condition of being incident.
INCIDENCE, ANGLE OF: See ANGLE OF INCIDENCE.
INCIDENCE, PLANE OF: See PLANE OF INCIDENCE.
INCIDENT: Approaching, striking, entering.
INCIDENT RAY: That ray which is approaching or entering.
INCLUSIONS: Lumps of improper materials found in optical glass.
INDEX OF REFRACTION: A number, applied to a medium, indicating its power to change the velocity of light. It is the ratio of the velocity of light in free space to its velocity in the given medium.
INFINITY: The extreme point of distance, limitless distance.
INFRARED LIGHT: Light whose wave-length is just beyond the receptive power of the human eye. Light of wave-length 8000 Å–200,000 Å.
INSTRUMENT, BINOCULAR: See BINOCULAR INSTRUMENT.
INSTRUMENT, OPTICAL: See OPTICAL INSTRUMENT.
INTENSITY: In light, its brightness, or strength.
INTERFERENCE: That phenomenon of light in which one wave train will superimpose upon another and cause either increase or decrease in intensity according to the phase relation of the two wave trains.
INTERFEROMETER: An optical instrument which makes use of the phenomenon of interference to make precise measurements of distance.
INTERPUPILLARY ADJUSTMENT: Adjustment of a binocular instrument so that the two eyepieces are at the proper separation for the eyes of the user.
INTERPUPILLARY DISTANCE: The distance between the centers of the pupils of the two eyes of an individual. It varies, between individuals, from 58–74 mm.

INVERSION: In an image, turning about an axis lying in the plane of the image.
INVERSION, PLANE OF: See PLANE OF INVERSION.
INVERTED: Turned about an axis lying in the plane of the image.
INVERTED MICROSCOPE: A microscope where the optical system is below the stage, and objects are placed upon the stage and examined from beneath.
INVERTING EYEPIECE: See EYEPIECE, INVERTING.
IRIS: In the human eye, an annulus of smooth muscle lying upon and restricting the clear aperture of the lens.
IRIS DIAPHRAGM: See DIAPHRAGM, IRIS.
ISOTROPIC: The same in all directions.

JENA GLASS: The glass produced originally by O. Schott, of Jena, Germany, upon the specifications of Abbé. Glass made according to these formulae.

KELLNER EYEPIECE: See EYEPIECE, KELLNER.
KEPLERIAN TELESCOPE: See TELESCOPE, KEPLERIAN.
KILOMETER: A unit of distance, equal to 1000 meters, or about ⅗ miles.

LEAN: In an optical instrument, that condition in which the image is tipped to one side or the other. Tilt.
LEMAN PRISM: A prism sometimes used in binoculars, consisting of a roof and two other reflecting surfaces. It inverts in two planes and displaces but does not deviate the light.
LENS: The optical medium contained between two refracting surfaces. More loosely, a piece of glass or other optical material comprising two surfaces, whose purpose is to converge or diverge light.
LENS, ACHROMATIC: A lens which has been corrected for chromatic aberration for two wave-lengths of light.
LENS, APLANATIC: A lens which has been corrected for spherical aberration and coma.
LENS, APOCHROMATIC: A lens which has been corrected for chromatic aberration for three wave-lengths of light.
LENS, BROKEN CONTACT: A lens consisting of two or more components which are mounted close together, but not cemented.

LENS, CEMENTED: A lens consisting of two or more components which are cemented together.

LENS, CENTER: A lens sometimes found in eyepieces, placed between the field and the eye lenses.

LENS, COLLECTIVE: A converging lens placed in an optical system for the purpose of increasing the field of view and flattening the field. It is usually a plano-convex lens, is part of the objective system, and is customarily placed at or near the image plane.

LENS, CONCENTRIC: A lens whose two centers of curvature are coincident.

LENS, CONTACT: A type of correction lens which is placed in contact with the eyeball.

LENS, CONVERGING: A lens which converges light. It is thicker at the center than at the edge.

LENS, CORRECTED: A lens which has been designed to be free of certain aberrations.

LENS, CORRECTING: A lens sometimes found in range finders, which forms a part of one of the objective systems. It is adjustable in position and serves to equalize the focal length of the two objectives.

LENS, CYLINDRICAL: A lens, one or both of whose surfaces is a portion of a cylinder.

LENS, DIVERGING: A lens which diverges light. It is thicker at the edge than at the center.

LENS, DOUBLE CONCAVE: A lens both of whose surfaces are concave.

LENS, DOUBLE CONVEX: A lens both of whose surfaces are convex.

LENS, DOUBLET: A lens consisting of two separated components.

LENS, ERECTING: A lens which performs the function of erecting the image.

LENS ERECTING SYSTEM: See ERECTING SYSTEM, LENS.

LENS, EYE: That lens of an eyepiece which is closest to the eye.

LENS, FIELD: That lens of an eyepiece which is nearest the objective of the instrument.

LENS, MENISCUS: A lens the curvatures of both of whose surfaces are in the same direction.

LENS, MINUS: A diverging lens. Its focal length is negative.

LENS, NEGATIVE: A lens whose focal length is negative. A diverging lens.
LENS, OBJECTIVE: That lens of an optical instrument which collects the light from an object-point.
LENS OF ZERO CURVATURE: A meniscus lens whose both surfaces have the same radius of curvature. Its focal length is infinity; refracting power, zero.
LENS, ORTHOSCOPIC: A lens which has been especially corrected for distortion.
LENS, PHOTOMACROGRAPHIC: A lens for the purpose of forming enlarged images of an object upon a photographic plate or film.
LENS, PLANO-CONVEX: A lens consisting of one convex and one plane surface.
LENS, PLANO-CONCAVE: A lens consisting of one concave and one plane surface.
LENS, PLUS: A lens whose focal length is positive. A converging lens.
LENS, POSITIVE: A lens whose focal length is positive. A converging lens.
LENS, PROJECTION: A lens for the purpose of projecting enlarged images upon a screen.
LENS, SYMMETRIC: A lens which has equal and opposite curvatures. It may be double convex or double concave.
LENS, TELEPHOTO: A camera lens of long focal length but so designed that the distance from lens to focal plane (back focal length) is shorter than the equivalent focal length.
LENS, THICK: A term applied to lenses when the separation of the two surfaces is taken into account.
LENS, THIN: A term applied to an imaginary lens which has no thickness.
LENS, TORIC: A lens whose one or both surfaces are toric curves, that is, have a different radius of curvature in different planes.
LENS, TRIPLET: A lens consisting of three components.
LEVEL VIAL: A glass tube containing a liquid, used for the purpose of determining a level line.
LIGHT, CONVERGING: See CONVERGING LIGHT.
LIGHT, DIVERGING: See DIVERGING LIGHT.
LIGHT, INFRARED: See INFRARED LIGHT.
LIGHT, PARALLEL: See PARALLEL LIGHT.

LIGHT, POLARIZED: See POLARIZED LIGHT.
LIGHT, ULTRAVIOLET: See ULTRAVIOLET LIGHT.
LIMIT, RAYLEIGH: See RAYLEIGH LIMIT.
LINE, CHARACTERISTIC FOCAL: See CHARACTERISTIC FOCAL LINE.
LINE, FRAUNHOFER: See FRAUNHOFER LINE.
LINE OF SIGHT: The line joining the eye and the object being observed. The direction of the optical axis of a telescope.
LINE, SPECTRAL: See SPECTRAL LINE.
LINEAR MAGNIFICATION: Ratio of size of image to object, measured perpendicular to the optical axis.
LONGITUDINAL MAGNIFICATION: The ratio of size of image to object, measured along the optical axis.
LUMINOUS: Giving off light.

MACULA LUTEA: An area in the eye where distinct vision is attained. It contains the fovea centralis, or area of most distinct vision.
MAGNIFICATION: Change in real or apparent size of an image with respect to its object.
MAGNIFICATION, ANGULAR: See ANGULAR MAGNIFICATION.
MAGNIFICATION, LINEAR: See LINEAR MAGNIFICATION.
MAGNIFICATION, LONGITUDINAL: See LONGITUDINAL MAGNIFICATION.
MAGNIFICATION, VARIABLE: See VARIABLE MAGNIFICATION.
MAGNIFYING POWER: The ability of an instrument or a lens to magnify an object.
MARGINAL FOCUS: The point where the marginal rays, or rays passing an optical element near its edge, are brought to a focus.
MARGINAL RAYS: Those rays which pass an optical element near its edge.
MECHANICAL AXIS: An axis determined by mechanical rotation or geometrical form, as, the mechanical axis of a telescope is the center line of its outside housing.
MEDIUM: In optics, any substance or space in which light travels.
MEDIUM, IMAGE: See IMAGE MEDIUM.

MEDIUM, OBJECT: See OBJECT MEDIUM.
MENISCUS LENS: See LENS, MENISCUS.
MERIDIANAL RAYS: Those rays of an oblique bundle of light rays, which lie in the plane determined by the optical axis and the chief ray of the bundle.
METALLURGICAL MICROSCOPE: A microscope used for the examination of metallurgical specimens, including certain special accessories for this purpose.
METER: A unit of measurement, equal to 39.37 inches. The basis of the metric system of measurement.
MICRO-COMPARATOR: A special microscope, made with two objectives and one eyepiece, for the comparison of two objects.
MICROMETER: An instrument for measuring accurate distances. A scale sometimes found on optical instruments where the fractional rotation of a worm shaft is indicated.
MICROSCOPE: An optical instrument for the examination of nearby objects under high magnification.
MICROSCOPE, BINOCULAR: See BINOCULAR MICROSCOPE.
MICROSCOPE, COMPOUND: See COMPOUND MICROSCOPE.
MICROSCOPE, DISSECTING: See DISSECTING MICROSCOPE.
MICROSCOPE, INVERTED: See INVERTED MICROSCOPE.
MICROSCOPE, METALLURGICAL: See METALLURGICAL MICROSCOPE.
MICROSCOPE, OIL-IMMERSION: See OIL-IMMERSION MICROSCOPE.
MICROSCOPE, PETROGRAPHIC: See PETROGRAPHIC MICROSCOPE.
MICROSCOPE, POLARIZING: See POLARIZING MICROSCOPE.
MICROSCOPE, SIMPLE: See SIMPLE MICROSCOPE.
MICROSCOPE, STEREOSCOPIC: See STEREOSCOPIC MICROSCOPE.
MIL: A unit of angular measurement, equal to 1/6400th of a circle.
MIL SYSTEM: That system of angular measurement making use of the mil.

MILLIMETER: A unit of linear measurement equal to 1/10 of a centimeter. Equal to 0.039 inches.

MINUS LENS: See LENS, MINUS.

MIRAGE: An optical illusion, due to special conditions of the atmosphere, when objects beyond the horizon become visible.

MIRROR: A surface prepared for the purpose of reflecting light.

MIRROR, FRONT-SURFACED: See FRONT-SURFACED MIRROR.

MIRROR, TRIPLE: See TRIPLE MIRROR.

MOUNTING: A mechanical device for holding an optical instrument.

MOUNTING, ALTAZIMUTH: See ALTAZIMUTH MOUNTING.

MOUNTING, EQUATORIAL: See EQUATORIAL MOUNTING.

MICROTOME: A machine for slicing very thin specimens for microscopic examination.

MUSCLE, CILIARY: See CILIARY MUSCLE.

MUSCLE, OBLIQUE: See OBLIQUE MUSCLE.

MUSCLE, RECTUS: See RECTUS MUSCLE.

MYOPIA: Nearsightedness.

NEAR POINT: That point for which the eye is focused when accommodation is exerted to its extreme value. It varies with age, but at maturity is about 8–10 inches.

NEARSIGHTEDNESS: That condition in which the near point of the eye is closer than normal. Myopia.

NEGATIVE EYEPIECE: See EYEPIECE, NEGATIVE.

NEGATIVE LENS: See LENS, NEGATIVE.

NERVE, OPTIC: See OPTIC NERVE.

NEURONE: A body cell which is part of the nervous system, a brain cell.

NEWTONIAN TELESCOPE: See TELESCOPE, NEWTONIAN.

NEWTON'S RINGS: Fringe patterns seen when two optical surfaces are placed together. Interference fringes.

NODAL PLANE: The perpendicular plane through a nodal point of an optical system.

NODAL POINTS: Two such points in an optical system in which the convergence angle of a ray incident at one point is

equal to the convergence angle of the refracted ray from the other point.

NORMAL: A perpendicular.

NUMERICAL APERTURE: A measure of the resolving power of a microscope. It is equal to n sin η where η is the angular semidiameter of the entrance pupil as seen from the object.

OBJECT: The thing of which an optical system is forming an image.

OBJECT MEDIUM: The medium containing the object.

OBJECT PLANE: The plane containing the object.

OBJECT-POINT: A point of which an optical system is forming an image.

OBJECT SPACE: The space containing the object.

OBJECT, VIRTUAL: See VIRTUAL OBJECT.

OBJECTIVE: See LENS, OBJECTIVE.

OBJECTIVE LENS: See LENS, OBJECTIVE.

OBJECTIVE, OIL-IMMERSION: See OIL-IMMERSION OBJECTIVE.

OBLIQUE ABERRATION: An aberration pertaining to extra-axial image-points, that is, an aberration of oblique bundles.

OBLIQUE BUNDLE: A bundle of light rays not parallel to the optical axis.

OBLIQUE MUSCLE: A muscle of the eye whose function it is to rotate the eyeball.

OBLIQUE PENCIL: A pencil of light rays not parallel to the optical axis.

OBLIQUE RAYS: Light rays not parallel to the optical axis.

OCULAR: Pertaining to the eye. An eyepiece.

OCULAR PRISM: A prism, found in range finders, located just beneath the eyepiece, whose function it is to present the images to the eyepiece in the proper aspect.

OCULAR, SOLID: See SOLID OCULAR.

OIL-IMMERSION MICROSCOPE: A microscope containing an oil-immersion objective.

OIL-IMMERSION OBJECTIVE: A microscope objective designed to work with a drop of oil between the objective and the slide. This type of objective has a larger numerical aperture than a "dry" objective, and permits higher magnification.

OPAQUE: Does not transmit light.

OPAQUE PROJECTOR: An optical instrument designed to project enlarged images of opaque objects upon a screen.

OPHTHALMIC: Pertaining to the study of the human eye.

OPHTHALMOMETER: An optical instrument designed to measure the curvature of the cornea of the eye.

OPTIC NERVE: The nerve connecting the retina of the eye with the brain.

OPTICAL AXIS: The line containing the optical centers of the elements of a centered optical system.

OPTICAL BENCH: A laboratory device for the purpose of mounting lenses for demonstration.

OPTICAL CENTER: A point with respect to a lens such that each light ray passing through this point enters and leaves the lens along parallel paths.

OPTICAL ELEMENT: A component of an optical system; a lens, mirror, prism, etc.

OPTICAL GLASS: Glass of special quality produced for the purpose of making optical elements.

OPTICAL INSTRUMENT: An instrument making use of light to perform its functions.

OPTICAL PATH: The distance, measured in wave-lengths, along a ray of light.

OPTICAL ROTATION: Rotation of the plane of polarization of a beam of light by certain types of minerals.

OPTICAL SINE CONDITION: A mathematical condition which indicates the perfection of an optical system.

OPTICAL SYSTEM: A combination of optical elements working together to produce a desired effect.

ORTHOSCOPIC: Especially corrected for distortion.

ORTHOSCOPIC EYEPIECE: See EYEPIECE, ORTHOSCOPIC.

ORTHOSCOPIC LENS: See LENS, ORTHOSCOPIC.

ORTHOSCOPY: Freedom from distortion.

OVERCORRECTED: Having a residual of negative aberration.

PANORAMIC TELESCOPE: An optical instrument so designed that its direction of view may be rotated through 360° without motion of the eyepiece.

PARALLAX: The condition which exists when two objects do not lie in the same plane, when the eye is shifted from side to side, the two objects appear to shift with respect to one an-

other; especially with respect to the reticle of a telescope and the image of the field of view.

PARALLEL LIGHT: A beam of light where the rays are all parallel to one another, the wave fronts being plane surfaces. Light emitted from an object at infinity.

PARAXIAL: Pertaining to the thin, threadlike region immediately surrounding the optical axis.

PARAXIAL FOCUS: The focus of rays in the paraxial region.

PARAXIAL RAYS: Rays in the paraxial region.

PATH, OPTICAL: See OPTICAL PATH.

PENCIL: A bundle of light rays.

PENCIL, AXIAL: See AXIAL PENCIL.

PENCIL, OBLIQUE: See OBLIQUE PENCIL.

PENTA PRISM: A prism, having five sides, which deviates light through a given angle and produces no inversion.

PERISCOPE: An optical instrument designed for looking over the top of obstacles without revealing the observer.

PETROGRAPHIC MICROSCOPE: A polarizing microscope.

PHASE: Aspect; condition. In particular, any given part of a light wave which is being considered.

PHOTOELECTRIC EFFECT: That effect produced by a beam of light upon certain materials, where electrons are given off upon absorption of the light.

PHOTOGRAPH: A permanent recording of an optical image made by the use of certain light-sensitive chemicals.

PHOTOMACROGRAPHIC LENS: See LENS, PHOTOMACROGRAPHIC.

PINHOLE CAMERA: A camera made of a light-tight box containing a pinhole in one of the sides.

PLANE: A surface such that a line joining any two of its points lies entirely within the surface. A flat surface.

PLANE, FOCAL: See FOCAL PLANE.

PLANE, IMAGE: See IMAGE PLANE.

PLANE, NODAL: See NODAL PLANE.

PLANE, OBJECT: See OBJECT PLANE.

PLANE OF INCIDENCE: The plane defined by the incident ray and the normal to the surface at the point of contact.

PLANE OF INVERSION: That plane defined by the perpendicular to the axis of inversion of an image and the optical axis.

PLANE-PARALLEL PLATE: A transparent plate, both of whose sides are plane and parallel to one another.

PLANE, PRINCIPAL: See PRINCIPAL PLANE.

PLANE TABLE: An instrument used in field mapping, consisting of a drawing table and a sighting telescope.

PLANO-CONCAVE LENS: See LENS, PLANO-CONCAVE.

PLANO-CONVEX LENS: See LENS, PLANO-CONVEX.

PLATE, PLANE PARALLEL: See PLANE-PARALLEL PLATE.

PLATE, SURFACE: See SURFACE PLATE.

PLUS LENS: See LENS, PLUS.

POINT, APLANATIC: See APLANATIC POINT.

POINT, FAR: See FAR POINT.

POINT, FOCAL: See FOCAL POINT.

POINT, IMAGE: See IMAGE POINT.

POINT, NEAR: See NEAR POINT.

POINT, OBJECT: See OBJECT-POINT.

POLARIMETER: An optical instrument for determining the optical rotation of a sample of material.

POLARISCOPE: An instrument for viewing objects under polarized light.

POLARIZATION: The production of light which is vibrating in a particular plane.

POLARIZED LIGHT: Light which is vibrating in a particular plane only.

POLARIZER: A device for producing polarized light.

POLARIZING MICROSCOPE: A microscope for examining specimens under polarized light.

POLAROID: Iodo-sulfate of quinine, prepared in a special form for producing polarized light.

POLE: That point of a lens surface which intersects the optical axis.

PORRO PRISM: A prism developed by M. Porro. Essentially a right-angle prism used in a particular way.

PORRO PRISM ERECTING SYSTEM: See ERECTING SYSTEM, PORRO PRISM.

POSITIVE EYEPIECE: See EYEPIECE, POSITIVE.

POSITIVE LENS: See LENS, POSITIVE.

POWER, DIOPTRIC: See DIOPTRIC POWER.

POWER, MAGNIFYING: See MAGNIFYING POWER.

POWER, REFRACTING: See REFRACTING POWER.

POWER, RESOLVING: See RESOLVING POWER.

POWER, STEREOSCOPIC: See STEREOSCOPIC POWER.

PRESBYOPIA: Loss of the power of accommodation of the eye.
PRINCIPAL AXIS: The line joining the centers of curvature of a lens, or joining the center of curvature and vertex of a mirror.
PRINCIPAL FOCUS: The focus of rays from an infinitely distant object-point.
PRINCIPAL PLANE: One of those two planes in a thick lens which represents the position of an equivalent thin lens.
PRISM: An optical element having two or more plane sides, not parallel to one another.
PRISM, ABBÉ: See ABBÉ PRISM.
PRISM, AMICI: See AMICI PRISM.
PRISM, BRASHEAR-HASTINGS: See BRASHEAR-HASTNGS PRISM.
PRISM, CONSTANT-DEVIATION: See CONSTANT-DEVIATION PRISM.
PRISM, DEVIATON: See DEVIATION PRISM.
PRISM, DISPLACEMENT: See DISPLACEMENT PRISM.
PRISM, DOVE: See DOVE PRISM.
PRISM, ERECTING: See ERECTING PRISM.
PRISM ERECTING SYSTEM: See ERECTING SYSTEM, PRISM.
PRISM, LEMAN: See LEMAN PRISM.
PRISM, OCULAR: See OCULAR PRISM.
PRISM, PENTA: See PENTA PRISM.
PRISM, PORRO: See PORRO PRISM.
PRISM, REFLECTING: See REFLECTING PRISM.
PRISM, ROOF: See ROOF PRISM.
PRISM, TOTAL REFLECTING: See TOTAL REFLECTING PRISM.
PROJECTION LENS: See LENS, PROJECTION.
PROJECTOR: An optical instrument designed to produce an enlarged image on a screen.
PROJECTOR, CONTOUR: See CONTOUR PROJECTOR.
PROJECTOR, OPAQUE: See OPAQUE PROJECTOR.
PROPAGATION: Generation; spreading; travel.
PUPIL, ENTRANCE: See ENTRANCE PUPIL.
PUPIL, EXIT: See EXIT PUPIL.

QUARTZ: A mineral possessing special optical properties.

RADIAN: Pertaining to a method of measuring angles using the radius as a unit. That angle subtended by a radius laid out along the circle. 57.3°.

RAMSDEN EYEPIECE: See EYEPIECE, RAMSDEN.

RANGE FINDER: An optical instrument for measuring distances, having two objectives separated by a considerable distance, the *base*.

RAY: A line representing the path of light.

RAY, INCIDENT: See INCIDENT RAY.

RAY, MERIDIANAL: See MERIDIANAL RAY.

RAY, PARAXIAL: See PARAXIAL RAY.

RAY, REFLECTED: See REFLECTED RAY.

RAY, REFRACTED: See REFRACTED RAY.

RAY, SAGITTAL: See SAGITTAL RAY.

RAY, TANGENTIAL: See TANGENTIAL RAY.

RAYLEIGH LIMIT: The condition laid down by Lord Rayleigh that images formed by an optical system would not differ sensibly from perfection if the rays composing them traveled over optical paths which did not differ by more than one-quarter of a wave-length.

REAL IMAGE: An image formed by the actual intersection of rays of light, as opposed to a virtual image, where the intersection is only apparent.

RECEPTOR: That part of the nervous system which receives stimuli.

RECTUS MUSCLE: A muscle whose function it is to rotate the eyeball.

RECIPROCAL: The quotient obtained by dividing unity by a number.

REFLECTED RAY: That ray which leaves a reflecting surface.

REFLECTING PRISM: A prism used in such a way that total reflection occurs at one of its faces.

REFLECTING TELESCOPE: See TELESCOPE, REFLECTING.

REFLECTION: That phenomenon of light in which a beam of light is turned back into the medium from which it came.

REFLECTION, ANGLE OF: See ANGLE OF REFLECTION.

REFLECTION, TOTAL: See TOTAL REFLECTION.

REFRACTED RAY: That ray which leaves a refracting surface.

REFRACTING ANGLE: The vertex angle of a prism or the angle between the two *refracting* faces.

REFRACTING POWER: The power of a lens to refract, or converge light. Dioptric power.

REFRACTING TELESCOPE: See TELESCOPE, REFRACTING.

REFRACTION: The bending of a ray of light upon its entering a different optical medium.

REFRACTION, ANGLE OF: See ANGLE OF REFRACTION.

REFRACTION, INDEX OF: See INDEX OF REFRACTION.

REFRACTIVE INDEX: See INDEX OF REFRACTION.

RESOLUTION: The degree to which detail is shown in an image.

RESOLVING POWER: The power of a lens or optical system to form separate images of close object-points.

RETAINING RING: A cylindrical mechanical part of an instrument whose function it is to hold another part in place.

RETICLE: A pattern etched on glass or fine wires strung upon a diaphragm, placed in an optical system at a point where a real image is formed, for the purpose of locating the optical axis or of making measurements.

RETINA: The light-sensitive coating on the interior of the eyeball which receives the images formed by the lens system of the eye.

RIGHT ASCENSION: One of the co-ordinates used for locating heavenly bodies. It is the angular distance, measured along the celestial equator, from the vernal equinox to the hour circle of the body in question.

RING, RETAINING: See RETAINING RING.

RINGS, NEWTON'S: See NEWTON'S RINGS.

ROD: One of the cells composing the retina of the eye.

ROOF PRISM: A prism containing a *roof,* or juncture of two reflecting surfaces at right angles, and whose line of juncture lies in the plane containing the incident chief ray. It inverts in two planes, and the roof itself deviates the light through 90°.

ROTATING PRISM: A movable prism in an instrument such as a panoramic telescope, for the purpose of rotating the image.

ROTATING WEDGE: A type of optical element found in range finders, consisting of a prism with a very small refracting angle, so arranged as to be rotated to change the deviation produced.

ROTATION, CENTER OF: See CENTER OF ROTATION.
ROTATION, OPTICAL: See OPTICAL ROTATION.
ROUGE: A compound used for the polishing of optical surfaces. Usually iron oxide.

SAGITTAL FOCUS: The focal point of the sagittal rays.
SAGITTAL RAYS: Those rays of an oblique bundle which lie in the plane perpendicular to the tangential plane.
SCALE, DIOPTER: See DIOPTER SCALE.
SCHMIDT CAMERA: A special type of astronomical telescope.
SCLEROTIC: The substance which forms the eyeball.
SCREW, SET: See SET SCREW.
SCREW, TANGENT: See TANGENT SCREW.
SECONDARY SPECTRUM: The residual chromatic aberration in an achromatic lens.
SEIDEL ABERRATIONS: Those aberrations defined by Baron von Seidel; spherical aberration, coma, astigmatism, distortion, curvature of field.
SET SCREW: A screw tapped into the threads of a cell or retaining ring to lock it in place.
/SEXTANT: An instrument for determining angles, used principally in navigation for measuring the altitude of heavenly bodies.
SHUTTER: A device for admitting light into an optical system for a specific length of time.
SIGHT, COLLIMATOR: See COLLIMATOR SIGHT.
SIGHT, LINE OF: See LINE OF SIGHT.
SIGHTING TELESCOPE: See TELESCOPE, SIGHTING.
SIMPLE EYEPIECE: See EYEPIECE, SIMPLE.
SIMPLE MICROSCOPE: A single lens used as a magnifier.
SIMPLE TELESCOPE: See TELESCOPE, SIMPLE.
SINE CONDITION: See OPTICAL SINE CONDITION.
SOLID OCULAR: An eyepiece composed of a single lens, usually of considerable thickness.
SPACE, IMAGE: See IMAGE SPACE.
SPACE, OBJECT: See OBJECT SPACE.
SPECTRAL LINE: The image of the slit produced by a spectroscope or spectrometer, whose position indicates the wave-length of the light.
SPECTACLES: Corrective lenses worn in front of the eyes for correcting vision.
SPECTROGRAPH: An instrument for photographing spectra.

SPECTROHELIOGRAPH: An instrument for photographing the sun in light of a specified wave-length.

SPECTROHELIOKINEMATOGRAPH: An instrument for taking motion pictures of the sun in light of a specified wave-length.

SPECTROHELIOSCOPE: An instrument for viewing the sun in light of a specified wave-length.

SPECTROMETER: An instrument for making measurements through the use of specified wave-lengths of light.

SPECTROSCOPE: An instrument for viewing a spectrum.

SPECTROSCOPY: The study and analysis of spectra.

SPECTRUM: The band of colored light or any part of it produced when the light from a given source is distributed by wave-length along a continuous band.

SPECTRUM, ABSORPTION: The spectrum produced by a substance which is absorbing specified wave-lengths of light from a source giving a continuous spectrum.

SPECTRUM, BRIGHT-LINE: The spectrum produced by a substance which is radiating with certain specific wave-lengths of light.

SPECTRUM, COMPARISON: A spectrum produced by a laboratory source, viewed or photographed beside a test spectrum for purposes of measurement and comparison.

SPECTRUM, CONTINUOUS: A spectrum containing all wave-lengths, and thus consisting of a continuous band.

SPECTRUM, DARK LINE: An absorption spectrum.

SPECTRUM, ELECTROMAGNETIC: See ELECTROMAGNETIC SPECTRUM.

SPECTRUM, EMISSION: A bright-line spectrum.

SPECTRUM, SECONDARY: See SECONDARY SPECTRUM.

SPECTRUM, VISIBLE: That part of the electromagnetic spectrum comprised of visible light, light to which the human eye is sensitive.

SPECTRUM, X-RAY: The spectrum produced by X-rays.

SPHERICAL ABERRATION: That aberration caused by the fact that rays passing through an optical element near its edge cross the axis nearer to the vertex than those passing the center.

STAGE: That part of a microscope upon which the specimen is mounted.

STEREOPSIS: The perception of depth arising as a result of binocular vision.

STEREOSCOPE: A device for viewing photographs taken with a stereoscopic camera, the combination of two views taken from slightly different positions producing stereoscopic effects.

STEREOSCOPIC EFFECT: STEREOPSIS.

STEREOSCOPIC MICROSCOPE: A microscope consisting of two complete optical systems by which a specimen is viewed with both eyes and stereoscopic effect achieved.

STEREOSCOPIC POWER: The ability of an individual to perceive depth as a result of binocular vision.

STEREOSCOPIC RANGE FINDER: A type of range finder in which the stereoscopic power of the observer is used to measure ranges.

STEREOSCOPIC VISION: Stereopsis.

STEREOVISION: Stereopsis.

STOP, APERTURE: See APERTURE STOP.

STOP DOWN: To reduce the aperture.

STOP, FIELD: See FIELD STOP.

STONES: Particles of undissolved material found in optical glass.

STRIAE: Veins found in optical glass, indicating regions of abnormal density.

STRAINS: Imperfections in optical glass caused by unequal cooling.

SUPERPOSITION: The combination of two wave trains of light, producing a combined wave by the principle of interference.

SURFACE PLATE: A metal plate, adjustable for leveling, often used for mounting instruments for adjustment.

SYMMETRIC ERECTING SYSTEM: See ERECTING SYSTEM, SYMMETRIC.

SYMMETRIC EYEPIECE: See EYEPIECE, SYMMETRIC.

SYMMETRIC LENS: See LENS, SYMMETRIC.

SYSTEM, ERECTING: See ERECTING SYSTEM.

SYSTEM, LENS ERECTING: See ERECTING SYSTEM, LENS.

SYSTEM, MIL: See MIL SYSTEM.

SYSTEM, OPTICAL: See OPTICAL SYSTEM.

TABLE, PLANE: See PLANE TABLE.

TANGENT SCREW: A screw, working against an arm and clamp, for making fine adjustments of rotation on an instrument.

TANGENTIAL FOCUS: The focus of tangential rays.

TANGENTIAL RAYS: MERIDIANAL RAYS.

TELEPHOTO LENS: See LENS, TELEPHOTO.

TELESCOPE: An optical system, composed of an objective and an eyepiece, and possible other elements, for the purpose of viewing distant objects. Strictly, an optical system whose focal length is infinity.

TELESCOPE, ASTRONOMICAL: A telescope used for astronomical observations; a telescope which does not contain an erecting system.

TELESCOPE, CASSEGRAINIAN: A reflecting telescope consisting of a paraboloidal primary mirror and a convex hyperboloidal secondary mirror.

TELESCOPE, COLLIMATING: A telescope with a tube which has been made concentric with its optical axis, used for adjusting instruments.

TELESCOPE, COMPOUND: A telescope containing an erecting system, as opposed to a simple telescope.

TELESCOPE, ELBOW: A telescope in which the optical axis makes a right-angle bend.

TELESCOPE, GALILEAN: A telescope consisting of a converging objective lens and a diverging eye lens. It gives an erect image without an erecting system.

TELESCOPE, GREGORIAN: A reflecting telescope consisting of a paraboloidal primary mirror and a concave ellipsoidal secondary mirror.

TELESCOPE, KEPLERIAN: A telescope consisting of a converging objective lens and a converging eyepiece.

TELESCOPE MOUNTING: A device for holding a telescope in its proper position, usually providing for rotation upon one or more axes.

TELESCOPE NEWTONIAN: A reflecting telescope consisting of a paraboloidal mirror and a prism or flat mirror for deviating the optical axis.

TELESCOPE, PANORAMIC: See PANORAMIC TELESCOPE.

TELESCOPE, REFLECTING: A telescope in which the objective is a mirror.

TELESCOPE, REFRACTING: A telescope in which the objective is a lens.

TELESCOPE, SIGHTING: A telescope used for sighting, as a gun.

TELESCOPE, SIMPLE: A telescope consisting of a single-lens objective and a single-lens eyepiece.

TELESCOPE, TERRESTRIAL: A telescope containing an erecting system.

TERRESTRIAL EYEPIECE: See EYEPIECE, TERRESTRIAL.

TERRESTRIAL TELESCOPE: See TELESCOPE, TERRESTRIAL.

THEODOLITE: An instrument used for making precise measurements of angles, usually used in surveying of land, etc.

THEOREM, OPTICAL SINE: See OPTICAL SINE CONDITION.

THICK LENS: See LENS, THICK.

THIN LENS: See LENS, THIN.

TILT: See LEAN.

TORIC LENS: See LENS, TORIC.

TOTAL REFLECTING PRISM: A prism where one of the faces produces total reflection.

TOTAL REFLECTION: Reflection occurring because of the critical angle of a medium, where a ray of light is unable to emerge from a surface, and is, therefore, reflected from it.

TRANSIT: A name applied generally to theodolites, although technically meaning a theodolite in which the telescope can be *plunged,* rotated through 180° on its horizontal axis.

TRANSLUCENT: Producing diffused light by transmission; light penetrates a translucent substance but an image cannot be transmitted.

TRANSPARENT: Pervious to light; light can pass through a transparent substance, and images can be transmitted through it.

TRANSVERSE CHROMATIC ABERRATION: That aberration by which image-points are rendered as tiny spectra, radial to the optical axis; chromatic aberration of magnification.

TRAVEL, HORIZONTAL: See HORIZONTAL TRAVEL.

TRAVEL, VERTICAL: See VERTICAL TRAVEL.

TRIPLE MIRROR: A prism composed of the corner of a cube. It is a constant-deviation prism for any ray of light whatever, producing a deviation of 180°. It inverts in one plane.

TRIPLET LENS: See LENS, TRIPLET.

ULTRA MICROSCOPE: A microscope using a dark-field condenser.

ULTRAVIOLET LIGHT: Light of wave-length slightly shorter than visible light. Light of wave-length of 200–4000Å.

UNDERCORRECTED: Having a residual of positive aberration.

VARIABLE MAGNIFICATION: A feature of some telescopes, made with adjustable erecting systems and/or eyepieces, which permit continuous variation of magnifiying power over a certain range.

VERNIER: A device for subdividing the smallest divisions of a scale.

VERTICAL ILLUMINATOR: A device used in microscopes, in which the light illuminating the slide is permitted to proceed down the tube of the instrument.

VERTICAL TRAVEL: Motion of an instrument in a vertical plane on its horizontal axis.

VIAL, LEVEL: See LEVEL VIAL.

VIEW, FIELD OF: See FIELD OF VIEW.

VIGNETTING EFFECT: The effect produced when the edges of the field of view are insufficiently illuminated with respect to the central portion. An effect produced by photographers, where there is a gradual fading off into the background.

VIRTUAL IMAGE: An image formed by the *apparent* intersection of light rays. A virtual image is produced by a plane mirror.

VIRTUAL OBJECT: An object (for an optical system) which is represented by the convergence of light rays which strike the optical system before arriving at their convergent point.

VISIBLE SPECTRUM: See SPECTRUM, VISIBLE.

VISION, DOUBLE: See DOUBLE VISION.

VISION, STEREOSCOPIC: See STEREOSCOPIC VISION.

VITREOUS HUMOR: A transparent, jellylike material which fills the eyeball behind the lens.

WAVE: A disturbance of a medium which is propagated from point to point continuously.

WAVE FRONT: The continuous locus of the points of an optical medium which are about to be disturbed; the locus of points representing the limit to which the disturbance (light) has reached at a given instant; the continuous locus of points which are in the same phase; a surface of equal phase.

WAVE-LENGTH: The distance between two similar points on successive waves.

WAVE NUMBER: The number of waves per centimeter.

WAVE TRAIN: A continuous set of waves.

WEDGE: A name given to a thin prism.

WEDGE, ROTATING: See ROTATING WEDGE.

WORM: A threaded portion of a shaft constituting an endless screw formed to mesh with a gear wheel.

WORM GEAR: A gear wheel formed to mesh with a worm.

WORM WHEEL: A worm gear.

X-RAYS: A portion of the electromagnetic spectrum, representing the radiation of very short wave-length, from 0.1 to 100Å.

X-RAY SPECTRUM: A spectrum produced by X-rays.

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